Climate Change Mitigation in the Context of Sustainable Development

New Insights, Challenges and Opportunities for Global Assessment Making

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Summary

The adoption of the Paris Agreement and the 2030 Agenda and its Sustainable Development Goals (SDGs) could make 2015 a defining year for setting human development on a more sustainable pathway. Both agendas are inextricably intertwined: On the one hand, unchecked climate change would be detrimental for sustainable and inclusive development around the world. This is why the global community committed to stay below a 2°C, possibly even below 1.5°C, rise in global mean temperature in the Paris Agreement, reflected in the 2030 Agenda (SDG #13). On the other hand, the Paris Agreement frames mitigation strongly in the context of sustainable development (SD). This is because climate policies – if designed poorly – could undermine SD in some non-climate dimensions but can otherwise yield substantial co-benefits for a number of SDGs. With such complex interactions between mitigation and SD, climate policy choices need to be informed by the best available science to harness synergies and address trade-offs across the many policy objectives.

This thesis analyzes the implications of assessing climate change mitigation pathways in the context of SD and discusses the limitations, challenges and opportunities of such an approach. Due to the complexity, uncertainty and value judgements inherent in climate change research, the thesis draws on insights from disciplines beyond climate economics, such as engineering, political science as well as the humanities. The different chapters provide complementary perspectives on the interaction between mitigation and SD arguing for a more integrated analysis of the two policy agendas. To that end, the thesis offers concrete insights for interdisciplinary bioenergy research, multi-objective welfare economics and energy-economy-climate modeling.

It develops, for example, a conceptual welfare-theoretic framework for better integrating insights on the interaction of mitigation and other sustainability objectives across different literature strands. It also shows that mitigation, in second-best settings, can have co-benefits for other sustainability goals with net welfare gains and can reduce short-term climate policy costs, particularly at the local and national level. Synthesizing the results of somewhat disparate strands of literature in a novel way confirms that reducing energy demand (e.g. via energy efficiency improvements) has highly synergistic effects. Taking an SD risk perspective reveals that weak short-term climate policies, particularly in combinations with technological constraints (e.g. on sustainable bioenergy potential), imply fewer synergies and substantial trade-offs.

The thesis argues that an informed public debate about such risk trade-offs can improve the choice of mitigation pathways. To inform an improved dialogue between scientists and policymakers, all chapters discuss the challenges around better synthesis and integration of scientific results. By drawing on a specific approach to the science-policy interface (SPI), all chapters of the thesis develop recommendations for global environmental assessments in the field of mitigation.

In its synthesis, the thesis highlights the challenges related to the unprecedented pace of knowledge production and points to both the raising complexity of embedding climate change research within a broader SD paradigm and the opportunities around an improved understanding of the SD implications of climate change mitigation. It concludes by questioning whether the current mandate of the Intergovernmental Panel on Climate Change provides the right setting to turn these challenges into opportunities for mitigation research and global assessment making.

ZUSAMMENFASSUNG

Die Verabschiedung des Pariser Klima-Abkommens und der Agenda 2030 mit den nachhaltigen Entwicklungsziele (SDGs) könnte 2015 zu einem entscheidenden Jahr machen, um Entwicklung auf einen nachhaltigeren Pfad zu setzen. Die beiden Politikagenden sind nicht voneinander zu trennen: Einerseits wäre ein unkontrollierter Klimawandel verheerend für einen nachhaltigen und inklusiven Entwicklungsfortschritt weltweit. Deshalb hat sich die Weltgemeinschaft im Pariser Abkommen das Ziel gesetzt, den Anstieg der globalen Durchschnittstemperatur auf 2°C, möglichst sogar auf 1,5°C, zu begrenzen, wie auch in der Agenda 2030 verankert (SDG #13). Gleichzeitig setzt das Pariser Abkommen Klimaschutz in den Kontext nachhaltiger Entwicklung. Denn Klimapolitik könnte bei schlechter Umsetzung die Erreichung einiger Entwicklungsziele in anderen Dimensionen gefährden, andernfalls aber zu erheblichem Nutzen für einige SDGs führen (*co-benefits*). Wegen dieser komplexen Verschränkungen zwischen Klimaschutz und nachhaltiger Entwicklung sind wissenschaftliche Erkenntnisse zentral für klimapolitische Entscheidungen, um vorhandene Synergien zu nutzen und Zielkonflikte zu berücksichtigen.

Die vorliegende Arbeit analysiert die Auswirkungen, die sich aus der Bewertung von Klimaschutzpfaden im Kontext nachhaltiger Entwicklung ergeben, und erörtert die Grenzen, Herausforderungen und Chancen eines solchen Vorgehens. Wegen der in den Klimawissenschaften inhärenten Komplexität, Unsicherheit und Werturteilen bedient sich die Arbeit der Einsichten auch jenseits der Klimaökonomie, beispielsweise der Ingenieurs-, Politik- und Geisteswissenschaften. Die verschiedenen Kapitel ergänzen sich in ihren Perspektiven auf das Zusammenspiel von Klimaschutz und nachhaltiger Entwicklung und fordern allesamt eine integrierte Analyse der zwei politischen Agenden. Dazu leistet die Arbeit mit konkreten Ergebnissen für interdisziplinäre Bioenergieforschung, Mehrziel-Wohlfahrtsökonomie und Klima-Energie-Ökonomie-Modellierung einen Beitrag.

Sie entwickelt zum Beispiel wohlfahrtstheoretische Überlegungen für eine bessere Berücksichtigung von Erkenntnissen aus dem Zusammenspiel von Klimaschutz und anderen Nachhaltigkeitszielen über verschieden Literaturstränge hinweg. Sie zeigt zudem, dass in sog. *second-best settings* Klimaschutz zu *co-benefits* für andere Nachhaltigkeitsziele mit einem Netto-Wohlfahrtsgewinn und zur Verringerung von kurzfristigen Klimaschutzkosten, insbesondere auf lokaler und nationaler Ebene, führen kann. Die Ergebnisse dieser zum Teil nebeneinanderstehenden Literaturstränge in innovativer Weise zu synthetisieren, bestätigt, dass niedrigerer Energieverbrauch (z. B. durch Energieeffizienzgewinne) hohe Synergieeffekte hat. Eine Risikoperspektive auf Nachhaltigkeitsziele verdeutlicht, dass geringe kurzfristige Klimaschutzambition, insbesondere in Verbindung mit technologischen Beschränkungen (z. B. für nachhaltiges Potential für Bioenergie), geringere Synergieeffekte und problematische Zielkonflikte nach sich ziehen können.

Die Arbeit argumentiert, dass eine sachlich fundierte öffentliche Debatte zu den Risikoabwägungen zwischen den klimarelevanten Nachhaltigkeitszielen zu verbesserten Entscheidungen über Klimaschutzpfaden führen kann. Um den Dialog zwischen Wissenschaft und Politik zu diesen Themen zu befördern, beschäftigen sich alle Kapitel mit den Herausforderungen einer besseren Synthese und Integration von Forschungsergebnissen. Auf Grundlage eines bestimmten Modells wissenschaftlicher Politikberatung entwickelt die Arbeit in allen Kapiteln Empfehlungen für *Global Environmental Assessments* im Bereich Klimaschutz.

In der Schlussbetrachtung werden die Herausforderungen der Wissensexplosion betont; zudem wird auf die steigende Komplexität verwiesen, diese neuen Erkenntnisse der Klimaforschung im Nachhaltigkeitsparadigma einzubetten, sowie auf die Chancen, die mit einem verbesserten Verständnis der Auswirkungen von Klimaschutz auf nachhaltige Entwicklung einhergehen. Schließlich stellt die Arbeit in Frage, ob das Mandat des IPCC derzeit noch die richtigen Rahmenbedingungen hergibt, diese Herausforderungen in Chancen für Klimaschutz-Forschung und *global assessment making* zu wandeln.

DANKSAGUNG

Es gibt viele Menschen, denen ich sehr dankbar dafür bin, dass sie mich bei der Entstehung der vorliegenden Arbeit begleitet haben. Statt sie aber hier einzeln zu würdigen, möchte ich die Erfahrungen aus meiner Zeit am Potsdam-Institut für Klimafolgenforschung (PIK), beim Intergovernmental Panel on Climate Change (IPCC) und am Mercator Research Institute for Global Commons and Climate Change (MCC) hervorheben, die für meine Arbeit besonders prägend waren.

Im PIK-Forschungsbereich *Nachhaltige Lösungen* hat mich sehr beeindruckt, mit welcher Selbstverständlichkeit das erworbene Wissen und die gesammelten Erfahrungen mit anderen Promovierenden geteilt und so vergrößert wurden. Dieser gemeinsame Lernprozess war nicht nur aufgrund der Interdisziplinarität, sondern auch aufgrund der kritischen Einstellung gegenüber den eigenen Ergebnissen und Methoden besonders intensiv. Diese offene Diskussionskultur macht für mich den Kern wissenschaftlichen Arbeitens aus und hat den Grundstein dafür gelegt, dass ich mich in meiner eigenen Arbeit bewusst mit unterschiedlichen Zugängen zu der Schnittstelle zwischen Klimaschutz und Nachhaltigkeit beschäftigt habe.

Als Scientist der *Technical Support Unit* (TSU) der Working Group III of the IPCC fand ich sehr ermutigend, wie selbstverständlich Wissenschaftler*innen über die verschiedenen Disziplinen, Kulturkreise, Sprachen und Persönlichkeiten hinweg kommuniziert haben – gute Argumente waren immer wichtiger als Rang und Namen. Diesen einmaligen Prozess miterleben und mitgestalten zu können, war eine besondere Erfahrung. Dabei war das Engagement meiner TSU-Kolleg*innen für mich eine große Motivation, so wie das Ringen um eine sinnvolle Aufteilung unserer gemeinsamen Arbeit lehrreich war. Viele der Ideen für die vorliegende Arbeit sind in der Auseinandersetzung mit den IPCC-Autor*innen und TSU-Kolleg*innen mit dem gemeinsamen Ziel entstanden, ein besseres Verständnis der vielen Verbindungslinien zwischen Klimaschutz und nachhaltiger Entwicklung zu erreichen.

Am MCC durfte ich schließlich daran mitwirken, Erfahrungen aus dem IPCC zu den Herausforderungen, wissenschaftliche Erkenntnisse zu aggregieren und synthetisieren, als Leitgedanken eines neuen Forschungsinstituts zu etablieren. Der Anspruch, klima- und wirtschaftswissenschaftliche Erkenntnisse auf Grundlage geisteswissenschaftlicher Überlegungen weiterzuentwickeln, hat mich inspiriert. Die vorliegende Arbeit unternimmt den Versuch, diesem Anspruch gerecht zu werden und profitiert davon, dass ich am Aufbau von zwei der MCC-Forschungsgruppen beteiligt gewesen bin.

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CONTENTS

1 Introduction

On 12 December 2015, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement (PA) in its 21st Conference of the Parties (COP21). After substantial disappointment with the process during COP15 in Copenhagen and many years of difficult negotiations, the PA has been highlighted as a major breakthrough in international climate diplomacy (Falkner, 2016; WBGU, 2016). The heart of the Agreement is the long-term goal to limit global temperature rise "to well below 2°C relative to pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015). World leaders thus provided a clear signal that they understand the high risks imposed by unabated climate change and that the world is united in this fight against climate change: all countries are now willing to make contributions to mitigation – despite the US announcement to leave the PA.

Commentaries and perspectives published after COP21 have debated both new opportunities arising from the PA as well as remaining reasons for concern, such as the insufficient ambition of the nationally determined contributions (NDCs) and the challenges of staying below 1.5°C (Hulme, 2016; Peters, 2016; Rogelj et al., 2016; Schleussner et al., 2016; Stern, 2016) – most recently assessed by the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018). But two aspects have received only little attention albeit being significant for the future of climate science and policy:

First, the goals of the PA are inextricably grounded in the long-standing dialogue between scientists and policymakers (Chapter 2). From the institutions on the boundary of climate science and policy, the Intergovernmental Panel on Climate Change (IPCC) stands out in terms of the breadth of its assessment scope and process design. Despite the IPCC crisis after COP15, the institution managed to reform itself (Ghaleigh, 2016; IAC, 2010) just in time to provide a credible platform for the important two-way interactions between policymakers and scientists (Cash et al., 2003; Edenhofer and Minx, 2014; Farrell and Jäger, 2006; Kowarsch et al., 2016), such as during the Structured Expert Dialogue between UNFCCC delegates and IPCC Co-/Vice-Chairs and Lead Authors (Rogelj and Knutti, 2016; Schleussner et al., 2016). Despite frustration with some aspects of its process (Carraro et al., 2015; Dubash et al., 2014; Victor et al., 2014), the IPCC as science-policy interface (SPI) seems to have worked well in dealing with a "wicked" problem like climate change (Pielke, 2007). But what can we learn from the past experience in this policy context for the future of global assessment making?

Second, the PA frames mitigation strongly in the context of sustainable development (SD). This is particularly obvious in its chapeau welcoming the UN 2030 Agenda for SD (UN, 2015). In fact, many of the most controversial discussions on the feasibility of mitigation pathways consistent with the 2°C limit are rooted in concerns about SD implications of large-scale mitigation actions (Anderson, 2015; Fuss et al., 2014; Geden, 2015; Smith et al., 2016). Unless mitigation pathways are in line with a wider set of SD goals including poverty eradication, reduced inequality within and between societies, affordable access to food, energy and water, the PA may not be acceptable to many. But how can mitigation research deal with the growing priority attached to the SD agenda?

These two questions are at the heart of this PhD thesis. On the one hand, it is concerned with how to assess and synthesize diverse strands of mitigation literature in order to provide *comprehensive* information to policymakers in an *objective* and *balanced* way (cf. the principles governing the work of the IPCC, 2013a). On the other hand, it is concerned with ways to embed mitigation research in a broader SD context and offers a sneak peek of the opportunities and challenges encountered when doing so. The introduction puts those themes in the context of the recent IPCC assessments and the broader literature and elaborates on the contributions of this thesis to existing research. Its aim is to serve as a learning exercise for prioritizing future mitigation research and improving global assessment making to inform robust climate and SD decision making.

1.1 The problems on the SPI & the promise of assessment making

The first cross-cutting theme of this thesis is how to adequately synthesize mitigation research and how global assessment making can learn from past experiences. Based on a reflection of the SPI in this section rooted in science studies as well as five years of scientific assessment experience working for the Technical Support Unit of IPCC Working Group III (WGIII), section 1.2 discusses both achievements and limitations of recent WGIII assessments. Such explicit reflection of the SPI can help deal with the challenges inherent in scientific policy advice (Kowarsch et al., 2017). For example, given the increasing complexity, deep uncertainty and contested values in many environmental policy fields (Funtowicz and Ravetz, 1993), particularly those related to climate change (Kowarsch, 2016), science studies points to various challenges in synthesizing scientific knowledge in ways that improve and facilitate evidence-based decision making (Jasanoff, 1994; Oreskes, 2004; Sarewitz, 2004; Weingart, 1999). These include:

i) the scientization of politics since the high complexity of many issues, particularly around climate change, requires decision makers to draw on scientific expertise – resulting in proxy debates on scientific issues in the political arena;
ii) political inaction justified by the prevailing uncertainty of scientific knowledge and the claim that more research will reach more actionable science over time;
iii) the politization of science since experts turned advocates extend the political controversies, often being about values at the core, into science – potentially resulting in even higher polarization, political gridlock and inaction.

To avoid such polarization, science studies point to various strategies how to best make use of science for the policy process (e.g. Brown, 2009; Jasanoff, 1994; Pielke, 2007). Out of those, large-scale global environmental assessments (GEAs) are a potentially powerful tool to realize the promises of evidence-based decision-making and avoid the pitfalls of polarizing use of science in politics since it can provide *relevant* synthesis of existing knowledge in a *credible* and *legitimate* way across scientific communities and competing worldviews (Cash et al., 2003; Keller, 2009; Mitchell et al., 2006).[1] This is due to a number of characteristics, including their:

[1] More general challenges for GEAs in light of the evolving international environmental governance landscape are discussed in Kowarsch et al. (2017), see Annex 8.3, co-authored by the candidate.

i) synthesis-driven approach to reduce the complexity and increase the *relevance* to the extent possible (Hulme and Mahony, 2010; Jasanoff and Wynne, 1998);
ii) comprehensive and transparent description of uncertainties to boost the *credibility* of the evidence (Mastrandrea et al., 2011; van der Sluijs et al., 2010);
iii) ability to identify implicit values and reconcile disparate viewpoints, e.g. by engaging multiple stakeholders thereby increasing the *legitimacy* of the process (Cash et al., 2003; Edenhofer and Kowarsch, 2015; Garard and Kowarsch, 2017).

Realizing the full potential of this particular way of organizing the SPI is, however, beset with many theoretical and practical challenges (Beck et al., 2014; Keller, 2009; Kowarsch et al., 2016; Mitchell et al., 2006). For example, the often cited criteria for guiding assessment making, i.e. *relevance*, *credibility*, and *legitimacy*, show trade-offs (Cash et al., 2003) and have a variety of meanings in different contexts (Heink et al., 2015). In the case of WGIII, the Co-Chairs and the TSU hence decided to help fostering discussions among the Lead Authors on the SPI to build a shared assessment philosophy.

This philosophy built on a specific vision for scientific policy advice, i.e. the pragmatic-enlightened model (PEM) which also serves as the normative anchor point in this thesis. It argues that science should provide key inputs into decision making by analysing alternative policy options and their practical consequences (rather than advocating a specific option, cf. the technocratic model discussed in Habermas, 1968). By highlighting potential implications of different *means* (e.g. mitigation pathways and technologies) to achieve alternative *ends* (e.g. long-term climate policy goals) it aims at informing public debates (Edenhofer and Kowarsch, 2015). In order to spell out the above criteria and operationalize the IPCC principles to provide a “comprehensive, objective and balanced view of the subject matter” (IPCC, 2013a, p. 2) in line with the PEM, seven criteria were presented and discussed that WGIII chapters would have to meet (see introduction to the so-called Wellington Agreement, co-authored by the candidate, see Annex 8.2):

i) Reviewing comprehensively the relevant scientific, technical and socio-economic literature;
ii) Describing consistent transformation pathways;
iii) Evaluating costs, risks and benefits of different pathways in a consistent way;
iv) Specifying underlying value judgements and worldviews;
v) Communicating quantitative and qualitative uncertainties;
vi) Using neutral language along good scientific practice;
vii) Making text, figures and tables accessible.

Since some criteria had already been integrated in existing IPCC procedures, e.g. the Expert Review to ensure a comprehensive literature coverage (IPCC, 2013a) or the Uncertainty Guidance Note (Mastrandrea et al., 2011) to ensure a common terminology for describing the results’ uncertainty, the conceptual discussions among WGIII AR5 Lead Authors focused on applying criteria 2)-4), i.e. assessing alternative transformation pathways by evaluating their practical consequences (i.e. their associated costs, risks and (co-)benefits) and making implicit value judgements transparent (IPCC, 2014a, Preface).

1.2 Assessing IPCC assessments

Based on these reflections of the SPI and drawing on insights from Chapters 2 and 3, the two following sub-sections discuss on a normative level to what extent the IPCC was successful in informing decision making about recent evidence without fostering polarization and political gridlock, focusing on the requirements of staying below 2°C and the contested role of bioenergy for climate change mitigation, respectively.

1.2.1 The economic and technological requirements of staying below 2°C

Drawing on the recent IPCC assessment results, Chapter 2 illustrates that the AR5 can serve as a good example of the labour division between scientists and decision makers as envisaged by the PEM. While the AR5 did not endorse any particular climate policy goal and thereby avoided taking a particular value judgement, it instead provided the negotiators with a map to navigate through the many relevant insights (cf. Hallegatte et al., 2016) to facilitate an informed public debate and a robust decision by policy makers.

The three IPCC WGs focused on different aspects of this knowledge map. While WGI, inter alia, provided temperature projections of alternative emission trajectories (see two exemplary Representative Concentration Pathways (RCPs) in the left panel of Figure 1.1), WGII assessed existing knowledge on the effects of increasing levels of warming on global climate-related risk dimensions (see synthesis graph in the right panel of Figure 1.1). Based on hundreds of mitigation scenarios from integrated energy-economy-climate models (or Integrated Assessment Models, IAMs), WGIII supplied results on the macroeconomic costs and technological challenges of staying below different warming levels to “facilitate an integrated and inclusive deliberation of alternative climate policy goals and the different possible means to achieve them” (IPCC, 2014a, p. ix).

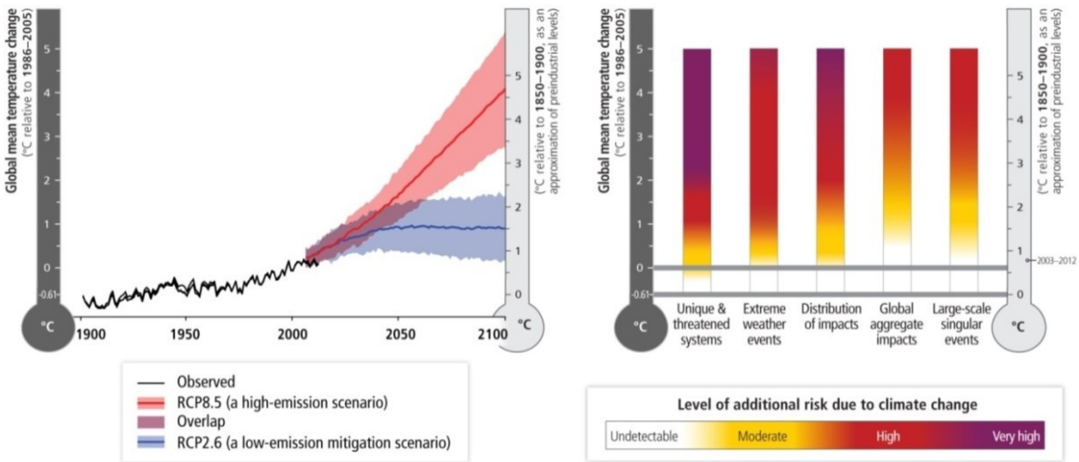

Figure 1.1 Past and projected global mean surface temperatures for two different RCPs are shown in the left panel. Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C), which is represented by the difference between the grey lines in the right panel. The colour shading indicates the additional risk due to increasing levels of climate change when a global temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple shows that very high risk is indicated by all specific criteria for key risks (see IPCC, 2014b for more details).

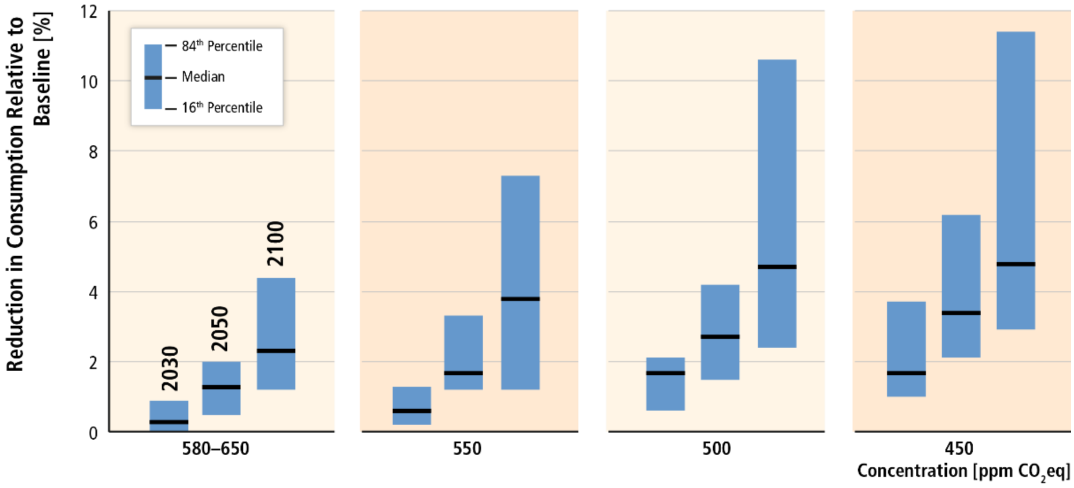

Figure 1.2 Global mitigation costs in cost-effective scenarios at different atmospheric concentrations levels in 2100, presented in percentage points of annualized consumption growth reductions relative to consumption growth in the baseline of 1.6 to 3% per year. Cost-effective scenarios assume immediate mitigation in all countries, a single global carbon price, and no additional limitations relative to the models' default technology assumptions. Cost estimates do not consider the benefits of reduced climate change nor co-benefits and adverse side-effects of mitigation (see IPCC, 2014b for more details).

As illustrated in Figure 1.2, global mitigation costs are relatively low (even for the most ambitious mitigation scenarios with atmospheric concentrations of 430-480 ppm CO_2eq) compared to global annual consumption growth in baseline scenarios of 1.6-3%. Chapter 2 argues that these IAM results were key for WGIII to describe consistent transformation pathways despite the limited information on the associated risks and co-benefits (see section 1.4).[2] Together with the insights provided by the other WGs, the Synthesis Report concluded that unabated climate change leads to "high to very high risks of severe, widespread and irreversible impacts", while the risks of 2°C pathways differ fundamentally from these in terms of their "nature, timescale, magnitude and persistence" (IPCC, 2014b, p. 77). Based on the scientific assessment of alternative transformation pathways provided by the AR5, the political decision at COP21 for aiming at staying below 2°C (and pursuing efforts to staying below 1.5°C) can hence be justified as an application of the precautionary principle (Knutti et al., 2016).

However, delaying stringent greenhouse gas (GHG) emissions reductions and limiting key mitigation technologies would both increase the costs and the technological challenges for staying below 2°C. Figure 1.3, for example, shows how CO_2 emissions reduction rates would have to increase much beyond historical developments and how much quicker low-carbon energy would have to be ramped up when delaying mitigation action. Based on these insights, Chapter 2 shows how the AR5 succeeded in pointing to the different costs and risks of alternative transformation pathways. It then discusses different rationales for unilaterally introducing carbon pricing, including co-benefits for other SD dimensions which could provide short-term entry points into these pathways (see section 1.4 below).

[2] The IAMs provided about 300 baseline (i.e. without additional climate policies) and 900 mitigation scenarios in a public database. They were run by computer-based models of long-term biogeophysical and human processes (see Chapter 5) providing information on, e.g. GHG emissions, energy technology deployment, resource use and trade, land-use change, and macroeconomic costs (Clarke et al., 2014). Synthesizing the information and integrating it with additional insights from other diverse, mostly bottom-up, mitigation research communities has been one of the major challenges of the past WGIII assessments.

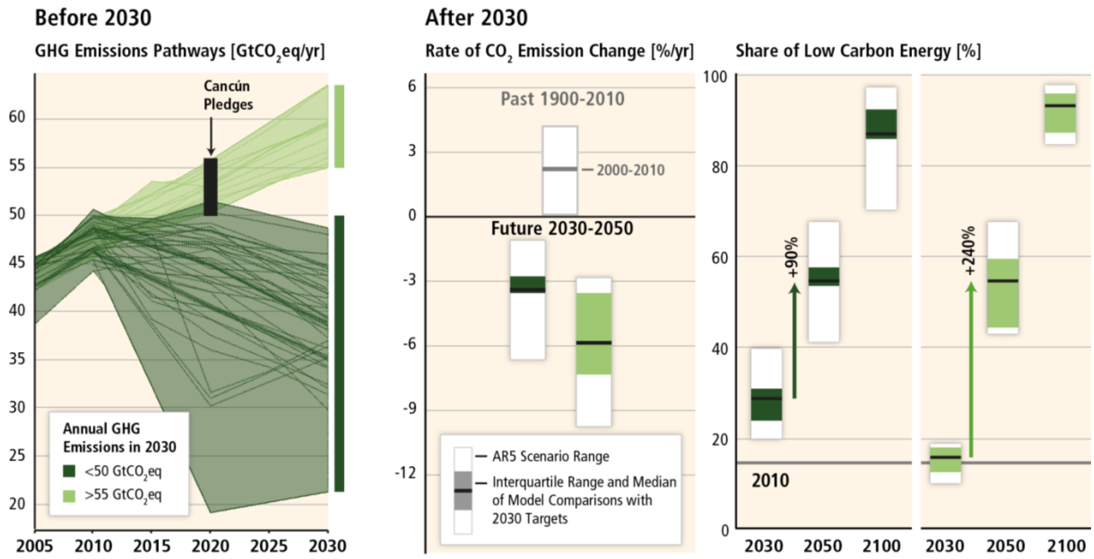

Figure 1.3 Technological challenges associated with the energy system transformation in terms of the average annual rate of CO_2 emissions reductions (2030-2050, middle panel) and low-carbon energy upscaling (2030-2050/2100, right panel) in mitigation scenarios consistent with staying below the 2°C limit with roughly >50% likelihood (left panel). Compared to immediate mitigation scenarios (dark green, GHG emissions <50 Gt CO_2-equivalent in 2030), delayed mitigation scenarios (light green, GHG emissions >55 Gt CO_2-equivalent) are characterized by much faster emissions reductions and upscaling of low-carbon energy technologies between 2030 and 2050. The black bar shows the uncertainty range of GHG emissions implied by the Cancún Pledges (see IPCC, 2014b for more details).

The final insight of Chapter 2 is the high reliance of 2°C pathways on bioenergy supply. This already features prominently in ambitious scenarios also due to the potential of bioenergy conversion processes to generate negative emissions via its combination with carbon capture and storage (BECCS) (Fuss et al., 2014). But bioenergy is projected to play an even more important role in delayed mitigation and 1.5°C scenarios, since many models do not find a solution without large-scale deployment of BECCS (Minx et al., 2017). As most other conceivable large-scale negative emissions technologies (NETs) also require large land areas (Smith et al., 2016), the availability of productive land is increasingly seen as a bottleneck for SD (see Obersteiner et al., 2016 and Chapter 6). Land as a fixed production factor has thus re-entered the economic literature (Mattauch, 2015; Smith, 1776) and questions the sustainability of some 2°C pathways.

1.2.2 The contested role of bioenergy for 2°C pathways

Against this background, it is worth noting that the global resource potential of bioenergy is a highly contested area of research due to competing resource needs (mainly land and water) and the associated SD risks (Chum et al., 2011). This leads to large ranges in future bioenergy supply projections (see Figure 1.4) being highly dependent on the chosen methods, assumptions and worldviews regarding the role of technological and lifestyle changes, as well as population and economic growth (Creutzig et al., 2014). Assessing the SD outcomes of alternative bioenergy deployment levels and reconciling the findings with IAM results was a key task for the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN). Based on the IPCC's own principles for assessment making (i.e. providing a comprehensive review of the relevant literature, identifying and possibly reconciling disparate views, and presenting the scientific content in a policy-relevant way, see section 1.1), Chapter 3 reviews to what extent the SRREN was able to live up to these standards.

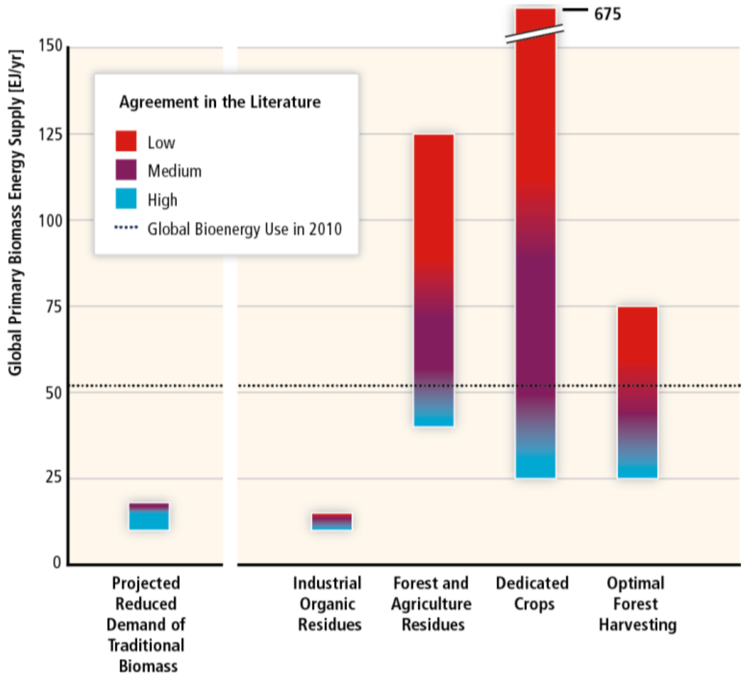

Figure 1.4 Ranges in the global technical bioenergy potential estimates by major resource category. The colour grading is intended to show qualitatively the degree of agreement in the estimates, from blue (large agreement in the literature) to purple (medium agreement) to red (small agreement). In addition, reducing traditional biomass demand by increasing its use efficiency could release the saved biomass for other energy purposes with large SD benefits (see Smith et al., 2014 for more details).

While the *Bioenergy* chapter (Chum et al., 2011) quite comprehensively reviewed existing literature and explicitly identified disparate viewpoints, the integration of the fragmented evidence was only partially successful across the entire report. For example, four alternative storylines with different future bioenergy deployment levels developed from bottom-up studies were not successfully integrated with transformation pathways based on IAM results. This lack of reconciliation was partly due to the IAM focus on "middle-of-the-road" development pathways, i.e. with little variance across relevant drivers of development, such as material/economic or environmental/social ways of living in a globally-oriented or a regionally-oriented world (IPCC, 2000). This made it difficult to map the top-down insights to the bottom-up literature whose findings partly depend on assumptions about the characteristics of development pathways (see Figure 3.4 in Chapter 3). In addition, there are substantial challenges to assess the globally aggregated SD effects of bioenergy supply as they not only differ across location and production contexts, but also across methodological approaches. This makes any meaningful assessment of the costs, risks and benefits of future bioenergy demand for mitigation pathways very demanding. Yet, such short- to medium-term effects on, e.g. food security and livelihoods matter most for millions (Creutzig et al., 2013).

Taking the contested role of bioenergy for ambitious mitigation as example, Chapter 3 teaches us that socially acceptable climate policy requires a better understanding of the broader SD implications of alternative 2°C pathways. This is even more relevant for 1.5°C pathways requiring large-scale deployment of negative-emission technologies (NETs) with potentially stark SD effects (IPCC, 2018; Minx et al., 2017). Based on these findings, this thesis argues that mitigation research and assessment making increasingly needs to broaden its perspective to multiple sustainability objectives.

1.3 Conceptualizing the link between mitigation and SD

Appropriately dealing with multiple objectives in mitigation research, the second cross-cutting theme of this thesis, first requires a conceptually sound understanding of SD. To put the most common definition from the Brundtland report[3] into economic language, SD can be said to follow a trajectory whose aggregate welfare level will never fall behind today's (Weitzman, 2003). Looking at the many conceptualizations for sustainability in the literature reveals, however, that there is neither agreement about the different arguments in this hypothetical welfare function nor about the way it should be aggregated (Fleurbaey, 2009; Jakob and Edenhofer, 2014; Kolstad et al., 2014). Chapter 4 thus argues that there is no clear guidance for choosing particular mitigation pathways from existing welfare economics literature and stresses the need to develop theoretical approaches to better conceptualize the link between mitigation and SD.

Since it is beyond the scope of this thesis to offer a new welfare theory of SD, Chapter 4 aims at offering first insights on the link between mitigation and SD building on existing theoretical approaches (see also Dasgupta, 2001; Fleurbaey, 2009; UNDP, 2010; Weitzman, 2003). While the concept of 'planetary boundaries' (Rockström et al., 2009; Steffen et al., 2015) is only touched upon due to its biophysical focus (van Vuuren et al., 2016), Chapter 4 puts mitigation research in the context of weak and strong sustainability (e.g. Neumayer, 2003) as this allows us to understand changes in social, economic and natural resource availability in economic welfare terms.

As outlined in Chapter 4, the weak sustainability approach rests on the assumption that different types of capital, i.e. physical, social and natural, can be substituted with each other and aims at sustaining the aggregate stock of capital for future generations. Strong sustainability, however, implies that the degradation of a particular capital stock beyond a certain threshold cannot be substituted by accumulation of other capital stocks and thus detoriates a society's capacity to sustain welfare. The chapter shows in an innovative way that these two paradigms can be reconciled in a simple welfare-theoretic framework based on the *net national product* concept (cf. Weitzman, 1976). This welfare-theoretic framework also helps understanding different mitigation literature strands in terms of their underlying assumptions about the concept of sustainability.

For example, following Weitzman (2009) and its 'dismal theorem', i.e. assuming an expected value of infinity for the stochastic discount factor, implicitly rejects weak sustainability. This favours a cost-effectiveness analysis (CEA) for studying climate policies. In such a strong sustainability framework, social welfare optima are calculated subject to GHG concentration targets that are imposed as boundary conditions beyond which climate impacts may cross certain tipping points (IPCC, 2013b; Lenton et al., 2008). In contrast, the assumption that catastrophic events are unlikely for reasonable temperature projections implies that a cost-benefit-analysis (CBA) yields an optimal balance between mitigation and adaptation efforts as well as residual climate impacts, according to the chosen social welfare function (Nordhaus, 2010) – implicitly assuming

[3] "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

substitutability between different types of capital. Yet, there is no consensus among scientists as to which framework is more appropriate, which is due to different interpretation of the scientific evidence on climate impacts and associated risk perceptions (see section 4.2 in Chapter 4).

Interestingly, both approaches are applied in scientific policy advice but in different policy contexts. On the one hand, information from CEA-based integrated models have been among the most important inputs into the past IPCC WGIII reports (e.g. Clarke et al., 2014; Fisher et al., 2007) which have been used to analyze the global challenges of staying below alternative temperature limits. Along these lines, the UNFCCC objective of 'avoiding dangerous anthropogenic interference with the climate system' (UNFCCC, 1992) can be seen as a normative interpretation of a strong sustainability approach and the 2°C and 1.5°C limits as its operationalization in the context of mitigation. On the other hand, results from CBA-based studies are necessary for estimating the social costs of carbon (SCC), i.e. the net present value of climate damages from an additional ton of carbon emitted to the atmosphere, conditional on a given global emissions trajectory over time. Although covering a large uncertainty range and attracting heavy criticism from prominent (climate) economists, these estimations represent the most comprehensive welfare analysis of different levels of GHG emissions control and play an important role in some countries' legislation processes (see Section 4.3.1 in Chapter 4).

Yet, a consistent multi-objective welfare analysis of multiple SD and climate policies is even more complex, since it would necessitate analysis in so-called second-best settings: If two or more externalities are not fully internalized, first-best solutions are no longer optimal (Lipsey and Lancaster, 1956). This implies that dealing with one policy problem at a time is unlikely to yield the welfare optimum. Instead, a comprehensive welfare analysis to improve public policy in a multi-objective context would need to take into account multiple externalities as well as multiple policy instruments and their interactions (see Figure 1.5 and a detailed discussion in Edenhofer et al., 2013).

For example, this implies that the values for the SCC assuming a second-best setting could be higher than those values calculated for a 'first-best world' as the latter often do not take into account the potential welfare gains (or losses) for other objectives. The difference may not be considerable in many environmental policy problems as the substances in question are confined to specific processes or sectors (e.g. O_3 or SO_2). But CO_2 pervades the entire economy making these effects relatively more important.

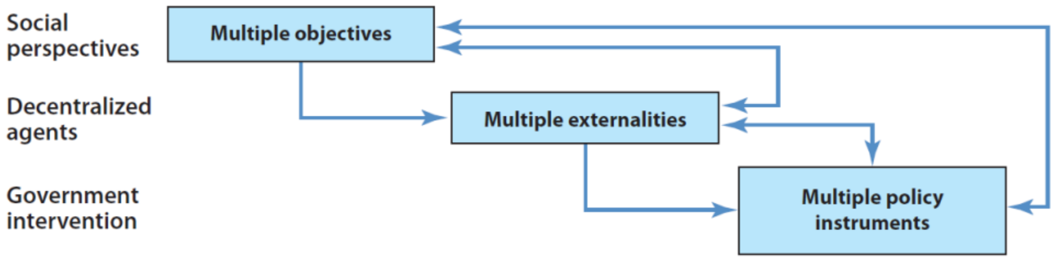

Figure 1.5 A public policy framework for dealing with multiple objectives in second-beset settings. Multiple objectives can lead to multiple externalities when decentralized agents lack the appropriate incentives to achieve these goals, i.e. if they are not fully internalized by existing policy instruments. Used with permission of Annual Reviews, from Edenhofer et al., 2013 On the Sustainability of Renewable Energy Sources. *Annu. Rev. Environ. Resour.* 38: 169–200; permission conveyed in 2022 through Copyright Clearance Center, Inc.

In a cost-effectiveness setting, this would imply that staying below a specific temperature limit would be cheaper if such positive effects were taken into account. This is the logic behind comments calling for a more prominent consideration of the positive and negative co-effects of mitigation on additional sustainability objectives (i.e. co-benefits and adverse side-effects, see Allwood et al., 2014) since the positive welfare effects of particular co-benefits may even outweigh the mitigation costs in the short term (Edenhofer et al., 2013; OECD, 2000; West et al., 2013). While raising the question if other policy instruments may achieve these welfare benefits at lower costs, Chapter 4 points to the fact that climate economics has not given enough attention to such questions (see also Nemet et al., 2010; Siegmeier et al., 2015).

Although welfare economics do not yet provide the tools to appropriately analyze such welfare effects, Chapter 4 argues that mitigation can have co-benefits for other sustainability objectives with net welfare gains until the optimal levels of mitigation and other objectives are reached. Yet, the prospect of achieving co-benefits ought not to divert attention from aiming at pathways that contribute to social welfare across all SD dimensions. But since co-benefits from mitigation can help achieving other sustainability objectives and hold the prospect of reducing the short-term costs of climate policies on the local/national level, the concept has been increasingly in the focus of academic and political discussions. Presenting the available information in a more structured way to decision makers could help guiding mitigation choices by facilitating a more informed public debate on mitigation choices (Fleurbaey et al., 2014; Jakob and Steckel, 2016; McCollum et al., 2018).

1.4 Synthesizing literature strands integrating mitigation and SD

According to the vision for scientific policy advice inspired by the PEM and laid out in section 1.1, the central objective of scientific assessments is to foster a more informed public debate about alternative pathways and their costs, (co-)benefits and risks on other goals. As discussed in sections 1.2 and 1.3, there are two major barriers to a comprehensive public debate.

i) First, both synergies and trade-offs between mitigation and sustainability objectives are key to understand the practical consequences of mitigation choices whereas existing literature or policy processes focus on either co-benefits or adverse side-effects. For example, the PA only explicitly highlights the positive aspects, recognizing “the social, economic and environmental value of voluntary mitigation actions and their co-benefits for adaptation, health and sustainable development” (UNFCCC, 2015, p. 15).
ii) Second, in the absence of a comprehensive theoretic underpinning, existing results from different literature strands of the co-effects of mitigation are difficult to reconcile. For example, having contributed to the WGIII AR5 assessment process, the candidate experienced the challenges in bringing experts from different disciplines together to work on shared definitions and problem framing.

As the WGIII AR5 assessment of existing scientific knowledge on the co-effects of mitigation for sustainability objectives advanced on both issues, it served as the natural starting point for this thesis' analysis and is briefly presented below.

1.4.1 Taking stock of IPCC AR5 – the co-effects of mitigation for SD

It is noteworthy that the WGIII AR5 provided both a social welfare and a SD framework for mitigation research in a multi-objective context, reviewed the literature on co-effects of mitigation technologies in different sectors as well as the global integrated model literature on co-effects of mitigation pathways – a major improvement from the IPCC AR4 (IPCC, 2007). But before being able to present hundreds of sectoral studies in a consistent way across sectors and to assess the uncertainty of the reported results, it took many meetings, discussions and iterations until the IPCC authors from different scientific disciplines finally agreed on workable definitions for '*co-benefits*', '*adverse side-effects*' and '*risk trade-offs*'. These definitions were required to capture the common understanding of the different scales and types of analysis as well as system boundaries:

Whereas technology experts focus on analyzing the co-effects of mitigation measures (i.e. technologies, processes and practices) on additional sustainability objectives, mostly in the context of specific sectors and locations, economists usually focus on analyzing economy-wide policy changes, the macroeconomic costs and their net effect on social welfare. This difference is reflected by Figure 1.6 which presents in the upper box the positive and negative co-effects of a measure aimed at objective A for additional objectives (B, C and D) irrespective of overall welfare effects, whereas the lower box represents the macroeconomic costs of the policy change (left circle) aimed at objective A. Evaluating the net effect on social welfare (right circle) then requires weighting the co-effects and costs in monetary terms. This would enable a more comprehensive comparison of the (opportunity) costs and (co-)effects of alternative policy choices.

Despite this better conceptualization, the increasing wealth of relevant literature and substantial efforts to integrate these sets of results, the WGIII AR5 provided an only limited synthesis as the information was scattered across several chapters. In effect, the report was not able to comprehensively evaluate alternative 2°C pathways with respect to their co-benefits and risks. Chapter 5 takes the AR5 as starting point and extends the synthesis of the co-effects of mitigation for SD, based on a conceptual welfare-theoretic framework. This framework serves as an organizational device for mapping the different literature strands and their respective contributions to a more holistic understanding of the social welfare effects of co-benefits and risks of mitigation for other sustainability objectives. Such an integrated perspective is key for robust decision making since it advances the understanding of the implications of alternative mitigation choices for broader sustainability objectives. Building on both a formalization and a graphic representation, this framework is able to relate the contributions of the individual strands to each other and reviews their contributions and limitations as well as the challenges of quantitative aggregation. The key insights are as follows:

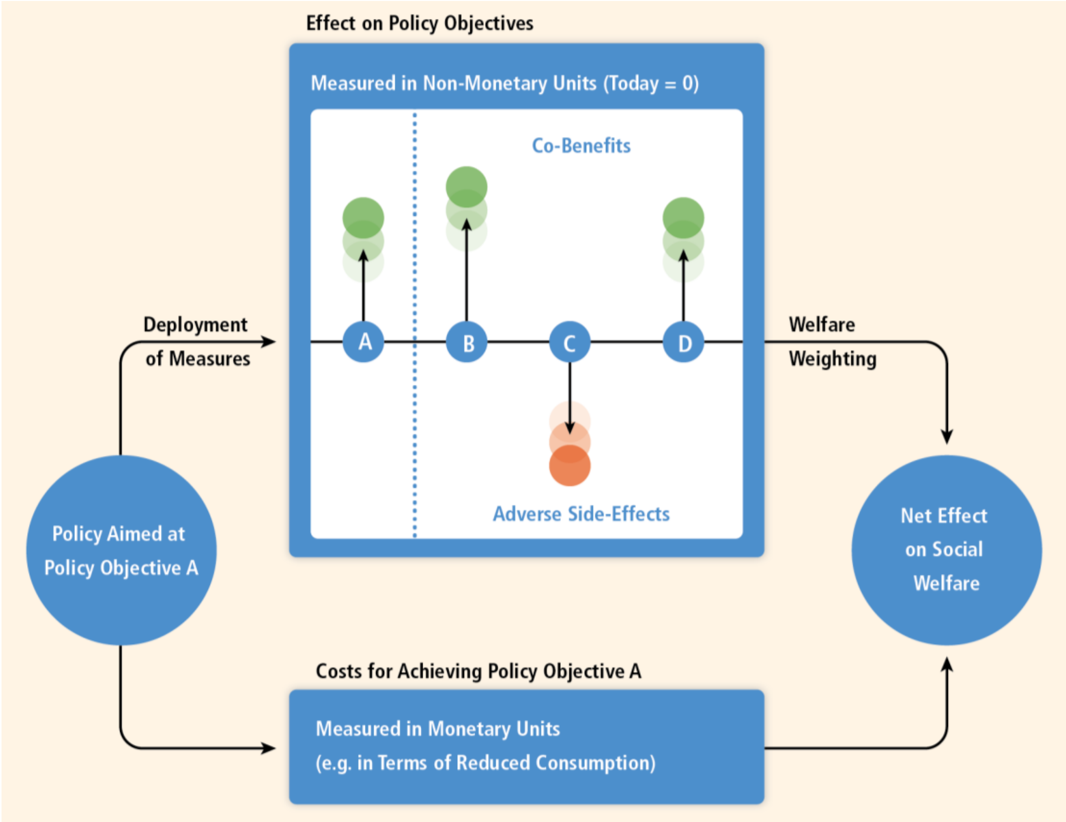

Figure 1.6 Schematic overview of the concepts around co-benefits, adverse side-effects and their effects on the macroeconomic costs of mitigation, additional sustainability objectives, and social welfare.

i. *Sectoral co-effect literature* focuses on analyzing the co-benefits and adverse side-effects of mitigation measures, implemented in a specific location, on additional non-climate sustainability objectives – both within and outside the sector or location (see Table 1.1 for a synthesis provided by WGIII AR5). The results are mostly reported in non-monetary metrics and it is difficult to gain more than qualitative insights for the co-effects of the same technology implemented elsewhere because quantifiable results depend largely on the chosen system boundaries for a specific study. The main insight from this strand at an aggregate level is that improving energy efficiency and reducing sectoral energy demand are robust strategies across multiple sustainability objectives whereas the co-effects of switching to low-carbon fuels are more complex.

ii. *Integrated model co-effect literature* analyzes the effects of stylized climate policies (see Figure 1.7 for an example from WGIII AR5) on the economy as well as their co-effects on additional non-climate policy objectives. While the mitigation costs are reported in monetary units (see Table S-6.1 in Chapter 6 on the different metrics used depending on model type), the associated co-effects are reported in non-monetary terms. While these studies take into account cross-sectoral and cross-regional interactions – a prerequisite of globally cost-effective mitigation pathways – they do not explicitly take into account interactions of climate and non-climate policies due to the mitigation focus.

iii. *Multi-objective integrated model literature (CEA-based)* analyzes integrated climate and non-climate policies and their effects on multiple sustainability objectives. Similar to choosing alternative GHG concentration levels as boundary conditions for the optimization, the existing studies consider alternative policy packages for non-climate objectives of varying stringencies. Given these boundaries, the most cost-effective pathways are calculated avoiding an explicit analysis of externalities and welfare optima. Due to rising complexities in the manifold interactions, this strand focused only on a few SD policy objectives finding mitigation to be a good entry point for sustainable energy objectives.

iv. The only *multi-objective integrated model (CBA-based) study* analyzes the costs and benefits of introducing integrated policies for additional sustainability objectives by monetizing and weighting the different effects on a number of objectives. The existing study explicitly considers multiple externalities and the welfare-optimizing pathway to internalize them. While it is able to incorporate many necessary steps of a full-fledged multi-objective welfare analysis, the results importantly rest on the chosen values, parameters and functions.

Table 1.1 Potential co-benefits (blue) and adverse side effects (red) of key sectoral mitigation measures. The uncertainty qualifiers between brackets denote the level of evidence (l = limited, m = medium, r = robust) and agreement (l = low, m = medium, h = high) on the respective effect (see IPCC, 2014b).

Sectoral mitigation measures	Effect on additional objectives/concerns		
	Economic	Social	Environmental
Energy Supply	*For possible upstream effects of biomass supply for bioenergy, see AFOLU.*		
Nuclear replacing coal power	Energy security (reduced exposure to fuel price volatility) (m/m); local employment impact (but uncertain net effect) (l/m); legacy/cost of waste and abandoned reactors (m/h)	Mixed health impact via reduced air pollution and coal mining accidents (m/h), nuclear accidents and waste treatment, uranium mining and milling (m/l); safety and waste concerns (r/h); proliferation risk (m/m)	Mixed ecosystem impact via reduced air pollution (m/h) and coal mining (l/h), nuclear accidents (m/m)
Renewable energy (wind, PV, CSP, hydro, geothermal, bioenergy) replacing coal	Energy security (r/m); local employment (but uncertain net effect) (m/m); water management (for some hydro energy) (m/h); extra measures to match demand (for PV, wind, some CSP) (r/h); higher use of critical metals for PV and direct drive wind turbines (r/m)	Reduced health impact via reduced air pollution (except bioenergy) (r/h) and coal mining accidents (m/h); contribution to (off-grid) energy access (m/l); threat of displacement (for large hydro installations) (m/h)	Mixed ecosystem impact via reduced air pollution (except bioenergy) (m/h) and coal mining (l/h), habitat impact (for some hydro energy) (m/m), landscape and wildlife impact (m/m); lower/higher water use (for wind, PV (m/m); bioenergy, CSP, geothermal and reservoir hydro (m/h))
Fossil energy with CCS replacing coal	Preservation vs. lock-in of human and physical capital in the fossil industry (m/m); long-term monitoring of CO_2 storage (m/h)	Health impact via risk of CO_2 leakage (m/m) and additional upstream supply-chain activities (m/h); safety concerns (CO_2 storage and transport) (m/h)	Ecosystem impact via additional upstream supply-chain activities (m/m) and higher water use (m/h)
CH_4 leakage prevention, capture or treatment	Energy security (potential to use gas in some cases) (l/h)	Reduced health impact via reduced air pollution (m/m); occupational safety at coal mines (m/m)	Reduced ecosystem impact via reduced air pollution (l/m)
Transport	*For possible upstream effects of low-carbon electricity, see Energy Supply. For biomass supply, see AFOLU.*		
Reduction of carbon intensity of fuel	Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (m/m); technological spillovers (l/l)	Mixed health impact via increased/reduced urban air pollution by electricity and hydrogen (r/h), diesel (l/m); road safety concerns (l/l) but reduced health impact via reduced noise (l/m) of electric LDVs	Mixed ecosystem impact of electricity and hydrogen via reduced urban air pollution (m/m) and material use (unsustainable mining) (l/l)
Reduction of energy intensity	Energy security (reduced oil dependence and exposure to oil price volatility) (m/m)	Reduced health impact via reduced urban air pollution (r/h); road safety (crash-worthiness depending on the design of the standards) (m/m)	Reduced ecosystem and biodiversity impact via reduced urban air pollution (m/h)
Compact urban form and improved transport infrastructure Modal shift	Energy security (reduced oil dependence and exposure to oil price volatility) (m/m); productivity (reduced urban congestion and travel times, affordable and accessible transport) (m/h)	Mixed health impact for non-motorized modes via increased physical activity (r/h), potentially higher exposure to air pollution (r/h), reduced noise (via modal shift and travel reduction) (r/h); equitable mobility access to employment opportunities (r/h); road safety (via modal shift) (r/h)	Reduced ecosystem impact via reduced urban air pollution (r/h) and land use competition (m/m)
Journey distance reduction and avoidance	Energy security (reduced oil dependence and exposure to oil price volatility) (r/h); productivity (reduced urban congestion/travel times, walking) (r/h)	Reduced health impact (for non-motorized transport modes) (r/h)	Mixed ecosystem impact via reduced urban air pollution (r/h), new/shorter shipping routes (r/h); reduced land use competition from transport infrastructure (r/h)
Buildings	*For possible upstream effects of fuel switching and RES, see Energy Supply.*		
Reduction of GHG emissions intensity (e.g., fuel switching, RES incorporation, green roofs)	Energy security (m/h); employment impact (m/m); lower need for energy subsidies (l/l); asset values of buildings (l/m)	Fuel poverty alleviation via reduced energy demand (m/h); energy access (for higher energy cost) (l/m); productive time for women/children (for replaced traditional cookstoves) (m/h)	Reduced health impact in residential buildings and ecosystem impact (via reduced fuel poverty (r/h), indoor/outdoor air pollution (r/h) and UHI effect) (l/m); urban biodiversity (for green roofs) (m/m)
Retrofits of existing buildings Exemplary new buildings Efficient equipment	Energy security (m/h); employment impact (m/m); productivity (for commercial buildings) (m/h); less need for energy subsidies (l/l); asset value of buildings (l/m); disaster resilience (l/m)	Fuel poverty alleviation via reduced energy demand (for retrofits and efficient equipment) (m/h); energy access (higher housing cost) (l/m); thermal comfort (m/h); productive time for women and children (for replaced traditional cookstoves) (m/h)	Reduced health and ecosystem impact (e.g., via reduced fuel poverty (r/h), indoor/outdoor air pollution (r/h), UHI effect (l/m), improved indoor environmental conditions (m/h)); health risk via insufficient ventilation (m/m); reduced water consumption and sewage production (l/l)
Behavioural changes reducing energy demand	Energy security (m/h); less need for energy subsidies (l/l)		Reduced health and ecosystem impact (e.g., via improved indoor environmental conditions (m/h) and less outdoor air pollution (r/h))
Industry	*For possible upstream effects of low-carbon energy supply (incl. CCS), see Energy Supply and of biomass supply, see AFOLU.*		
Reduction of CO_2/non-CO_2 GHG emission intensity	Competitiveness and productivity (m/h)	Reduced health impact via reduced local air pollution and better working conditions (PFC from aluminium) (m/m)	Reduced ecosystem impact (via reduced local air and water pollution) (m/m); water conservation (l/m)
Technical energy efficiency improvements via new processes/technologies	Energy security (via lower energy intensity) (m/m); employment impact (l/l); competitiveness and productivity (m/h); technological spillovers in DCs (l/l)	Reduced health impact via reduced local pollution (l/m); new business opportunities (m/m); increased water availability and quality (l/l); improved safety, working conditions and job satisfaction (m/m)	Reduced ecosystem impact via reduced fossil fuel extraction (l/l) and reduced local pollution and waste (m/m)
Material efficiency of goods, recycling	Decreased national sales tax revenue in the medium term (l/l); employment impact (waste recycling) (l/l); competitiveness in manufacturing (l/l); new infrastructure for industrial clusters (l/l)	Reduced health impacts and safety concerns (l/m); new business opportunities (m/m) and reduced local conflicts (reduced resource extraction) (l/m)	Reduced ecosystem impact via reduced local air and water pollution and waste material disposal (m/m); reduced use of raw/virgin materials and natural resources implying reduced unsustainable resource mining (l/l)
Product demand reductions	Decreased national sales tax revenue in the medium term (l/l)	Increased wellbeing via diverse lifestyle choices (l/l)	Reduced post-consumption waste (l/l)
AFOLU	*Note: co-benefits and adverse side effects depend on the development context and the scale of the intervention (size).*		
Supply side: forestry, land-based agriculture, livestock, integrated systems and bioenergy Demand side: reduced losses in the food supply chain, changes in human diets and in demand for wood and forestry products	Mixed employment impact via entrepreneurship development (m/h), use of less labour-intensive technologies in agriculture (m/m); diversification of income sources and access to markets (r/h); additional income to sustainable landscape management (m/h); income concentration (m/m); energy security (resource sufficiency) (m/h); Innovative financing mechanisms for sustainable resource management (m/h); technology innovation and transfer (m/m)	Increased food-crops production through integrated systems and sustainable agriculture intensification (r/m); decreased food production (locally) due to large-scale monocultures of non-food crops (r/l); increased cultural habitats and recreational areas via (sustainable) forest management and conservation (m/m); improved human health and animal welfare (e.g., through less use of pesticides, reduced burning practices and agroforestry and silvo-pastoral systems) (m/h); human health impact related to burning practices (in agriculture or bioenergy) (m/m); mixed impacts on gender, intra- and inter-generational equity via participation and fair benefit sharing (r/h) and higher concentration of benefits (m/m)	Mixed impact on ecosystem services via large-scale monocultures (r/h), ecosystem conservation, sustainable management as well as sustainable agriculture (r/h); increased land use competition (r/m); increased soil quality (r/h); decreased erosion (r/h); increased ecosystem resilience (m/h); albedo and evaporation (r/h) Institutional aspects: mixed impact on tenure and use rights at the local level (for indigenous people and local communities) (r/h) and on access to participative mechanisms for land management decisions (r/h); enforcement of existing policies for sustainable resource management (r/h)

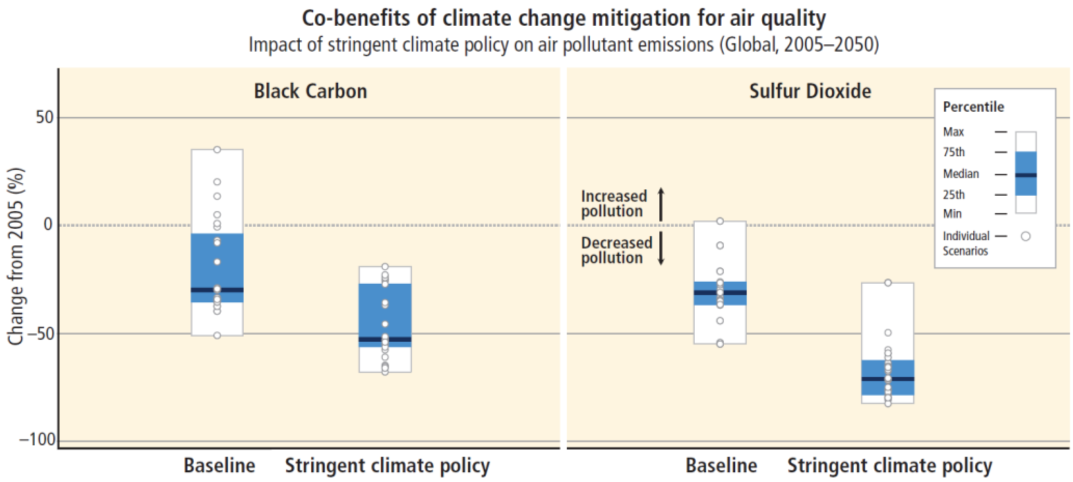

Figure 1.7 Co-benefits of stringent mitigation pathways for air quality in scenarios reaching concentrations of 430-530 ppm CO_2eq in 2100 (see IPCC, 2014b for more details).

1.4.2 Untapped potential for further synthesis across literature strands

Chapter 5 concludes that the evidence is still fragmented across different sectors, research communities, scales and types of analysis and only very few studies simultaneously address multiple objectives, externalities and policy instruments. While the multi-objective integrated model literature is the most comprehensive effort thus far in integrating mitigation and additional non-climate sustainability objectives into a welfare framework, the studies also show the limitations of expanding the system boundaries as they have to reduce the scope of analysis at each step (see Section 5.4.3 for a critical discussion of the abilities of integrated models to address welfare). Chapter 5 concludes that there is a trade-off between the number of objectives analyzed and the ability to present quantitative results, particularly for overall welfare implications on a global scale. At the same time, it argues that such an aggregation is "a prerequisite for a detailed understanding of the importance of global-scale synergies and trade-offs across mitigation and the many other global-scale sustainability objectives" (Chapter 5, p. 98).

Chapter 5 thus looks at another way to combine the results of the somewhat disparate strands of literature by drawing on their respective strengths, i.e. qualitative evidence on a broad set of sustainability objectives and quantitative multi-model results for future energy demand and supply taking into account cross-sectoral and cross-regional interactions for different scenarios. The synthesis figure places quantitative results from the integrated model literature next to qualitative results from the sectoral literature to improve the understanding of the magnitude of the expected co-effects.

Without conveying a non-existent level of knowledge and precision, this synthesis is able to point to robust results: improving energy efficiency and other means to reduce energy demand have synergistic effects across mitigation and many additional non-climate sustainability objectives on a global level. At the same time, this synthesis also reveals that the higher demand for bioenergy and low-carbon electricity to decarbonize the energy sector may lead to additional SD risks. This finding points to potentially important risk trade-offs across multiple sustainability objectives that can only be taken into account by decision makers if they can draw on robust assessments of climate and sustainability policies in an integrated way (cf. Hallegatte et al., 2016).

1.5 Taking a SD risk perspective on 2°C pathways

Despite the focus of integrated model literature on energy system transformation, they report a significant number of variables relevant for understanding both synergies and trade-offs from the different mitigation choices (see Table 6.1 in Chapter 6) that can be used to more systematically analyze the risks of alternative 2°C pathways for sustainability objectives. This can foster a more informed public debate about different clusters of 2°C pathways (see Chapter 5 and Jakob and Steckel, 2016) – acknowledging that the climate policy and the SDGs agendas are highly interconnected and should be tracked within a unified framework. But the literature that addresses the interlinkages comprehensively and in quantitative terms is still scarce – although increasingly progressing in that direction (see e.g. McCollum et al., 2018 and IPCC, 2018). To address that research gap, Chapter 6 complements existing literature by taking a risk perspective that scrutinizes how indicators relevant for a set of energy-related SDGs diverge from a counterfactual for different types of model constraints.

This is particularly relevant given that the nationally determined contributions (NDCs) are inconsistent with cost-effective 2°C pathways and further delaying more ambitious mitigation narrows the option space for staying below 2°C (Rogelj et al., 2016). In addition, the technology portfolio usually assumed to be fully available in 2°C pathways is likely to be constrained due to issues around public acceptance of significantly upscaling low-carbon technologies. Combining the two types of constraints can even lead to the inability of models to find a solution – implying that the 2°C limit is unlikely to be achieved in such situations, let alone returning to 1.5°C at the end of the century.

By systematically linking the chosen set of indicators to global SD risks, Chapter 6 is able to show a first but rough approximation of the implications of alternative clusters of 2°C pathways on energy-related SDGs. Although the presented results do not cover all relevant SDGs explicitly due to the limited data availability, it can foster a public debate on the interaction between SDGs and mitigation action. Figure 1.8 summarizes the key results by looking at the different clusters of model constraints relative to optimal 2°C pathways (i.e. those with immediate mitigation, full technology portfolios, and conventional energy demand growth). The most important insights are that lower energy demand growth reduces many SD risk levels but that technological constraints and weak short-term climate policies imply fewer synergies and substantial trade-offs.

This implies that climate and SD policies cannot be separated from each other any longer. Climate policy will not be successful unless it seriously considers SD implications. Dividing the huge effort of achieving more sustainable development pathways into isolated policy problems thus falls short of reaping synergies and successfully managing trade-offs across the many SDGs. Chapter 6 argues that reigning in global energy demand growth and raising short-term ambition beyond the NDCs not only improves the chances of staying below 2°C, possibly 1.5°C, but also the prospect of reaching other SDGs.

Figure 1.8 Changes in SD risk dimensions that can be linked to a set of SDGs and other sustainable energy objectives in constrained 2°C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth). Data taken from Figure 6.5 in Chapter 6.

At the same time, Chapter 6 acknowledges that the indicators taken from the integrated model results and used for the analysis are sometimes very rough representations of the underlying sustainability concerns. Given the increasing requirement of synthesizing knowledge across different strands of literature to more comprehensively answer upcoming questions about the sustainability of future developments pathways, research on mitigation and its SD implications increasingly needs to evolve in terms of appropriate indicators and system boundaries. Until more detailed results are available from ongoing and future research, this thesis' results are an important lens from which we can take a glimpse of the difficulties of integrating SD more effectively into the mitigation research design and, subsequently, into global scientific assessment making.

Due to the already broad scope of the thesis, other relevant drivers of human development at the nexus of climate and SD will not be discussed in the following chapters despite their relevance for mitigation policy choices (Jakob et al., 2014; Jakob and Steckel, 2014). These include inclusive access to basic infrastructure services (Calderón and Servén, 2004; Franks et al., 2018; Jakob et al., 2016; Steckel et al., 2017, 2013), the ability of developing countries to absorb large (climate) finance inflows (Jakob et al., 2015; Kornek et al., 2017; van der Ploeg, 2011), structural changes (Cohen, 2006; McMillan and Rodrik, 2011; Rodrik, 2016), distributional impacts and political economy issues (Inchauste and Victor, 2017; Sovacool, 2012; Sterner, 2012; Trebilcock, 2014).

1.6 Outline of the thesis

The structure of this thesis closely follows the guiding questions that were shown to be important implications from the PA for mitigation and SD research as well as its synthesis in global scientific assessments for informing robust decision-making:

1) How can global scientific assessment making evolve in the face of rising complexity and demands for solution-orientation to ensure that future assessment processes adequately synthesize diverse strands of mitigation research pathways and facilitate decision-making?
2) What new challenges arise when framing mitigation in the broader context of SD, i.e. taking into account multiple objectives, multiple externalities, and multiple policy instruments on multiple spatial and temporal scales?

The first part of this thesis mainly tackles the first question by assessing IPCC assessment and learning from previous experience. Chapters 2 and 3 demonstrate to what extent the SRREN and the WGIII AR5, respectively, have lived up to the PEM and the IPCC principles to provide a "comprehensive, objective and balanced view of the subject matter" (IPCC, 2013a) and points to the important role global scientific assessment can play. Recent developments have made the past experience all the more valuable: In October 2018, the IPCC Special Report on Global Warming of 1.5°C assessed the existing research on the 1.5°C limit (IPCC, 2018), the first report in its sixth assessment cycle to be concluded in 2022 – in time for the first full Global Stocktake (GST) as foreseen by the Paris Agreement.

At the same time, the 2030 Agenda is shaping local, national and global policy agendas and has put SD in the focus of mitigation research. The principal aim of the second part of the thesis is hence to develop a better understanding of the interaction between SD and mitigation research on a conceptual level (Chapter 4) and across literature strands (Chapter 5) to better understand co-benefits and risks of alternative mitigation pathways (Chapter 6).

Finally, Chapter 7 synthesizes the insights from the different chapters of this thesis, considers their implications for challenges and opportunities for global assessment making in the light of the surge in knowledge in the climate and SD literature, and concludes with an outlook for the next IPCC assessment cycle and future mitigation and SD research more broadly.

1.7 References

Allwood, J.M., Bosetti, V., Dubash, N.K., Gómez-Echeverri, L., von Stechow, C., 2014. Glossary, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 1249–1279.

Anderson, K., 2015. Duality in climate science. *Nat. Geosci.* 8, 898–900. https://doi.org/10.1038/ngeo2559

Beck, S., Borie, M., Chilvers, J., Esguerra, A., Heubach, K., Hulme, M., Lidskog, R., Lövbrand, E., Marquard, E., Miller, C., Nadim, T., Neßhöver, C., Settele, J., Turnhout, E., Vasileiadou, E., Görg, C., 2014. Towards a Reflexive Turn in the Governance of Global Environmental Expertise. The Cases of the IPCC and the IPBES. *GAIA - Ecol. Perspect. Sci. Soc.* 23, 80–87. https://doi.org/10.14512/gaia.23.2.4

Brown, M.B., 2009. *Science in Democracy: Expertise, Institutions, and Representation.* The MIT Press.

Calderón, C., Servén, L., 2004. The Effects of Infrastructure Development on Growth and Income Distribution. *Policy Research Working Papers*, The World Bank 1–43. https://doi.org/10.1596/1813-9450-3400

Carraro, C., Edenhofer, O., Flachsland, C., Kolstad, C., Stavins, R., Stowe, R., 2015. The IPCC at a crossroads: Opportunities for reform. *Science* 350, 34–35. https://doi.org/10.1126/science.aac4419

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci.* 100, 8086–8091. https://doi.org/10.1073/pnas.1231332100

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, G., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., Pingoud, K., 2011. Bioenergy, in: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 209–331.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B., van Vuuren, D.P., 2014. Assessing Transformation Pathways, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 413–506.

Cohen, B., 2006. Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technol. Soc., Sustainable Cities* 28, 63–80. https://doi.org/10.1016/j.techsoc.2005.10.005

Creutzig, F., Corbera, E., Bolwig, S., Hunsberger, C., 2013. Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environ. Res. Lett.* 8, 035047. https://doi.org/10.1088/1748-9326/8/3/035047

Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., Masera, O., 2014. Bioenergy and climate change mitigation: An assessment. *Glob Chance Biol Bioenergy* 7, 916–944. https://doi.org/10.1111/gcbb.12205

Dasgupta, P., 2001. *Human Well-Being and the Natural Environment.* Oxford University Press, New York, USA.

Dubash, N.K., Fleurbaey, M., Kartha, S., 2014. Political implications of data presentation. *Science* 345, 36–37. https://doi.org/10.1126/science.1255734

Edenhofer, O., Kowarsch, M., 2015. Cartography of pathways: A new model for environmental policy assessments. *Environ. Sci. Policy* 51, 56–64. https://doi.org/10.1016/j.envsci.2015.03.017

Edenhofer, O., Minx, J., 2014. Mapmakers and navigators, facts and values. *Science* 345, 37–38. https://doi.org/10.1126/science.1255998

Edenhofer, O., Seyboth, K., Creutzig, F., Schlömer, S., 2013. On the sustainability of renewable energy sources. *Annu. Rev. Environ. Resour.* 38, 169–200. https://doi.org/10.1146/annurev-environ-051012-145344

Falkner, R., 2016. The Paris Agreement and the new logic of international climate politics. *Int. Aff.* 92, 1107–1125. https://doi.org/10.1111/1468-2346.12708

Farrell, A.E., Jäger (Eds.), 2006. *Assessments of Regional and Global Environmental Risks: Designing Processes for the Effective Use of Science in Decisionmaking.* Resources for the Future, Washington, DC, USA.

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., De la Chesnaye, F., Hourcade, J.-C., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D., Warren, R., 2007. Issues Related to Mitigation in the Long-Term Context, in: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-Governmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-250.

Fleurbaey, M., 2009. Beyond GDP: The Quest for a Measure of Social Welfare. *J. Econ. Lit.* 47, 1029–1075. https://doi.org/10.1257/jel.47.4.1029

Fleurbaey, M., Kartha, S., Bolwig, S., Chee, Y.L., Chen, Y., Corbera, E., Lecocq, F., Lutz, W., Muylaert, M.S., Norgaard, R.B., Okereke, C., Sagar, A.D., 2014. Sustainable Development and Equity, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 283–350.

Franks, M., Lessmann, K., Jakob, M., Steckel, J.C., Edenhofer, O., 2018. Mobilizing domestic resources for the Agenda 2030 via carbon pricing. *Nat. Sustain.* 1, 350. https://doi.org/10.1038/s41893-018-0083-3

Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. *Futures* 25, 739–755. https://doi.org/16/0016-3287(93)90022-L

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. *Nat. Clim. Change* 4, 850–853. https://doi.org/10.1038/nclimate2392

Garard, J., Kowarsch, M., 2017. If at first you don't succeed: Evaluating stakeholder engagement in global environmental assessments. *Environ. Sci. Policy.* https://doi.org/10.1016/j.envsci.2017.02.007

Geden, O., 2015. Policy: Climate advisers must maintain integrity. *Nat. News* 521, 27. https://doi.org/10.1038/521027a

Ghaleigh, 2016. Science and Climate Change Law - The Role of the IPCC in International Decision-Making, in: Gray, K.R., Tarasofsky, R., Carlarne, C.P. (Eds.), *The Oxford Handbook of International Climate Change Law.* Oxford University Press, pp. 55–71.

Habermas, J., 1968. *Technik und Wissenschaft als »Ideologie«*, 19th ed. Suhrkamp Verlag.

Hallegatte, S., Rogelj, J., Allen, M., Clarke, L., Edenhofer, O., Field, C.B., Friedlingstein, P., van Kesteren, L., Knutti, R., Mach, K.J., Mastrandrea, M., Michel, A., Minx, J., Oppenheimer, M., Plattner, G.-K., Riahi, K., Schaeffer, M., Stocker, T.F., van Vuuren, D.P., 2016. Mapping the climate change challenge. *Nat. Clim. Change* 6, 663–668. https://doi.org/10.1038/nclimate3057

Heink, U., Marquard, E., Heubach, K., Jax, K., Kugel, C., Neßhöver, C., Neumann, R.K., Paulsch, A., Tilch, S., Timaeus, J., Vandewalle, M., 2015. Conceptualizing credibility, relevance and legitimacy for evaluating the effectiveness of science–policy interfaces: Challenges and opportunities. *Sci. Public Policy* 42, 676–689. https://doi.org/10.1093/scipol/scu082

Hulme, M., 2016. 1.5°C and climate research after the Paris Agreement. *Nat. Clim. Change* 6, 222–224. https://doi.org/10.1038/nclimate2939

Hulme, M., Mahony, M., 2010. Climate change: What do we know about the IPCC? *Prog. Phys. Geogr*. 34, 705–718. https://doi.org/10.1177/0309133310373719

IAC, 2010. *Climate change assessments, review of the processes and procedures of the IPCC*. InterAcademy Council (IAC), Amsterdam, The Netherlands.

Inchauste, G., Victor, D.G., 2017. *The Political Economy of Energy Subsidy Reform, Directions in Development - Energy and Mining*. The World Bank. https://doi.org/10.1596/978-1-4648-1007-7

IPCC, 2018. *Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014a. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014b. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC, 2013a. *Procedures for the preparation for the review, acceptance, adoption, approval and publication of IPCC reports*. Appendix A to the principles governing IPCC work.

IPCC, 2013b. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Bosch, A. Nauels, Y. Xia, B. Bex, B.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2000. *Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jakob, M., Chen, C., Fuss, S., Marxen, A., Rao, N.D., Edenhofer, O., 2016. Carbon Pricing Revenues Could Close Infrastructure Access Gaps. *World Dev.* 84, 254–265. https://doi.org/10.1016/j.worlddev.2016.03.001

Jakob, M., Edenhofer, O., 2014. Green growth, degrowth, and the commons. *Oxf. Rev. Econ. Policy* 30, 447–468. https://doi.org/10.1093/oxrep/gru026

Jakob, M., Steckel, J.C., 2016. Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.* 11, 104010. https://doi.org/10.1088/1748-9326/11/10/104010

Jakob, M., Steckel, J.C., 2014. How climate change mitigation could harm development in poor countries. *Wiley Interdiscip. Rev. Clim. Change* 5, 161–168. https://doi.org/10.1002/wcc.260

Jakob, M., Steckel, J.C., Flachsland, C., Baumstark, L., 2015. Climate finance for developing country mitigation: blessing or curse? *Clim. Dev.* 7, 1–15. https://doi.org/10.1080/17565529.2014.934768

Jakob, M., Steckel, J.C., Klasen, S., Lay, J., Grunewald, N., Martínez-Zarzoso, I., Renner, S., Edenhofer, O., 2014. Feasible mitigation actions in developing countries. *Nat. Clim. Change* 4, 961–968. https://doi.org/10.1038/nclimate2370

Jasanoff, S., 1994. *The fifth branch: science advisers as policymakers*, 1st Harvard University Press paperback ed. ed. Harvard University Press, Cambridge Mass.

Jasanoff, S., Wynne, B., 1998. Science and Decisionmaking, in: Rayner, S., Malone (Eds.), *Human Choice and Climate Change. Volume 1: The Societal Framework.* Battelle Press, Colombus, Ohio, pp. 1–87.

Keller, A.C., 2009. Credibility and Relevance in Environmental Policy: Measuring Strategies and Performance among Science Assessment Organizations. *J. Public Adm. Res. Theory*, 20(2): 357–386. https://doi.org/10.1093/jopart/mup001

Knutti, R., Rogelj, J., Sedlácek, J., Fischer, E.M., 2016. A scientific critique of the two-degree climate change target. *Nat. Geosci. 9*, 13–18. https://doi.org/10.1038/ngeo2595

Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Cariño Olvera, M., Fullerton, D., Gollier, C., Hanemann, W.M., Hassan, R., Jotzo, F., Khan, M.R., Meyer, L., Mundaca, L., 2014. Social, Economic and Ethical Concepts and Methods, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 207–282.

Kornek, U., Steckel, J.C., Lessmann, K., Edenhofer, O., 2017. The climate rent curse: new challenges for burden sharing. *Int. Environ. Agreem. Polit. Law Econ.* 17, 855–882. https://doi.org/10.1007/s10784-017-9352-2

Kowarsch, M., 2016. Policy assessments to enhance EU scientific advice. *Nat. Clim. Change* 6, 15–17. https://doi.org/10.1038/nclimate2835

Kowarsch, M., Garard, J., Riousset, P., Lenzi, D., Knopf, B., Harrs, J.-A., Edenhofer, O., 2016. Scientific assessments to facilitate deliberative policy learning. *Palgrave Commun.* 2, 16092. https://doi.org/10.1057/palcomms.2016.92

Kowarsch, M., Jabbour, J., Flachsland, C., Kok, M.T.J., Watson, S.R., Haas, P.M., Minx, J.C., Alcamo, J., Garard, J., Riousset, P., Pintér, L., Langford, C., Yamineva, Y., von Stechow, C., O'Reilly, J., Edenhofer, O., 2017. A road map for global environmental assessments. *Nat. Clim. Change* 7, 379–382. https://doi.org/10.1038/nclimate3307

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci.* 105, 1786–1793. https://doi.org/10.1073/pnas.0705414105

Lipsey, R.G., Lancaster, K., 1956. The general theory of second best. *Rev. Econ. Stud.* 24, 11–32. https://doi.org/10.2307/2296233

Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Edenhofer, O., Stocker, T.F., Field, C.B., Ebi, K.L., Matschoss, P.R., 2011. The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Clim. Change* 108, 675–691. https://doi.org/10.1007/s10584-011-0178-6

Mattauch, L., 2015. *Rent and Redistribution: The welfare implications of financing low-carbon public investment* (PhD thesis). Technische Universtität, Berlin.

McCollum, D.L., Echeverri, L.G., Busch, S., Pachauri, S., Parkinson, S., Joeri Rogelj, Krey, V., Minx, J.C., Nilsson, M., Stevance, A.-S., Riahi, K., 2018. Connecting the sustainable development goals by their energy inter-linkages. *Environ. Res. Lett.* 13, 033006. https://doi.org/10.1088/1748-9326/aaafe3

McMillan, M.S., Rodrik, D., 2011. Globalization, structural change and productivity growth. *National Bureau of Economic Research Working Paper*. https://doi.org/10.3386/w17143

Minx, J.C., Lamb, W.F., Callaghan, M.W., Bornmann, L., Fuss, S., 2017. Fast growing research on negative emissions. *Environ. Res. Lett.* 12, 035007. https://doi.org/10.1088/1748-9326/aa5ee5

Mitchell, R.B., Clark, W.C., Cash, D.W., Dickson, N.M. (Eds.), 2006. *Global Environmental Assessments: Information and Influence.* MIT Press, Cambridge, MA, USA.

Nemet, G.F., Holloway, T., Meier, P., 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environ. Res. Lett.* 5, 014007. https://doi.org/10.1088/1748-9326/5/1/014007

Neumayer, E., 2003. *Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms.* Edward Elgar Publishing.

Nordhaus, W.D., 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proc. Natl. Acad. Sci.* 107, 11721–11726. https://doi.org/10.1073/pnas.1005985107

Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S., van Vuuren, D., 2016. Assessing the land resource–food price nexus of the Sustainable Development Goals. *Sci. Adv.* 2. https://doi.org/10.1126/sciadv.1501499

OECD, 2000. *Ancillary Benefits and Costs of Greenhouse Gas Mitigation.* Proceedings of an IPCC Co-Sponsored Workshop, held on 27-29 March 2000, in Washington D.C. Organisation for Economic Co-operation and Development, Paris, France.

Oreskes, N., 2004. Science and public policy: What's proof got to do with it? *Environ. Sci. Policy, Science, Policy, and Politics: Learning from Controversy Over The Skeptical Environmentalist* 7, 369–383. https://doi.org/10.1016/j.envsci.2004.06.002

Peters, G.P., 2016. The "best available science" to inform 1.5°C policy choices. *Nat. Clim. Change* 6, 646–649. https://doi.org/10.1038/nclimate3000

Pielke, R.A.J., 2007. *The Honest Broker: Making Sense of Science in Policy and Politics.* Cambridge University Press.

Rockström, J., Steffen, W., Noone, K., Persson, Å, Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., others, 2009. A safe operating space for humanity. *Nature* 461, 472–475. https://doi.org/10.1038/461472a

Rodrik, D., 2016. Premature deindustrialization. *J. Econ. Growth* 21, 1–33. https://doi.org/10.1007/s10887-015-9122-3

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* 534, 631–639. https://doi.org/10.1038/nature18307

Rogelj, J., Knutti, R., 2016. Geosciences after Paris. *Nat. Geosci.* 9, 187–189. https://doi.org/10.1038/ngeo2668

Sarewitz, D., 2004. How science makes environmental controversies worse. *Environ. Sci. Policy* 7, 385–403. https://doi.org/10.1016/j.envsci.2004.06.001

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E.M., Knutti, R., Levermann, A., Frieler, K., Hare, W., 2016. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change* 6, 827–835. https://doi.org/10.1038/nclimate3096

Siegmeier, J., Mattauch, L., Franks, M., Klenert, D., Schultes, A., Edenhofer, O., 2015. A Public Finance Perspective on Climate Policy: Six Interactions That May Enhance Welfare. *Nota Lav. Fondazione Eni Enrico Mattei* 31, 1–44.

Smith, A., 1776. *An Inquiry into the Nature and Causes of the Wealth of Nations.* W. Strahan, London.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 811–922.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Change* 6, 42–50. https://doi.org/10.1038/nclimate2870

Sovacool, B.K., 2012. The political economy of energy poverty: A review of key challenges. *Energy Sustain. Dev.* 16, 272–282. https://doi.org/10.1016/j.esd.2012.05.006

Steckel, J.C., Brecha, R.J., Jakob, M., Strefler, J., Luderer, G., 2013. Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecol. Econ.* 90, 53–67. https://doi.org/10.1016/j.ecolecon.2013.02.006

Steckel, J.C., Rao, N.D., Jakob, M., 2017. Access to infrastructure services: Global trends and drivers. *Util. Policy* 45, 109–117. https://doi.org/10.1016/j.jup.2017.03.001

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347, 1259855. https://doi.org/10.1126/science.1259855

Stern, N., 2016. Economics: Current climate models are grossly misleading. *Nat. News* 530, 407. https://doi.org/10.1038/530407a

Sterner, T., 2012. F*uel Taxes and the Poor: The Distributional Effects of Gasoline Taxation and Their Implications for Climate Policy.* Routledge, Oxford, UK.

Trebilcock, M.J., 2014. *Dealing with Losers: The Political Economy of Policy Transitions.* Oxford University Press, New York, USA.

UN, 2015. *Transforming our world: the 2030 Agenda for Sustainable Development (A/RES/70/1).* Resolution adopted by the General Assembly on 25 September 2015.

UNDP, 2010. *Human Development Report 2010 The Real Wealth of Nations: Pathways to Human Development.* United Nations Development Program (UNDP), New York, USA.

UNFCCC, 2015. *Adoption of the Paris Agreement. (No. Report No. FCCC/CP/2015/L.9/Rev.1).* United Nations Framework Convention on Climate Change (UNFCCC).

UNFCCC, 1992. *United Nations Framework Convention on Climate Change* (No. Report No. FCCC/INFORMAL/84).

van der Ploeg, F., 2011. Natural Resources: Curse or Blessing? *J. Econ. Lit.* 49, 366–420.

van der Sluijs, J.P., van Est, R., Riphagen, M., 2010. Beyond consensus: reflections from a democratic perspective on the interaction between climate politics and science. *Curr. Opin. Environ. Sustain.* 2, 409–415. https://doi.org/10.1016/j.cosust.2010.10.003

van Vuuren, D.P., Lucas, P.L., Häyhä, T., Cornell, S.E., Stafford-Smith, M., 2016. Horses for courses: analytical tools to explore planetary boundaries. *Earth Syst Dynam* 7, 267–279. https://doi.org/10.5194/esd-7-267-2016

Victor, D.G., Gerlagh, R., Baiocchi, G., 2014. Getting serious about categorizing countries. *Science* 345, 34–36. https://doi.org/10.1126/science.1255302

WBGU, 2016. *Development and justice through transformation: The Four Big 'I's – A contribution to Germany´s G20 presidency in 2017 – Special Report 2016*. German Advisory Council on Global Change (WBGU), Berlin, Germany.

WCED, 1987. *Our Common Future, From One Earth to One World (Brundtland Report).* United Nations World Commission on Environment and Development (WCED), Oslo, Norway.

Weingart, P., 1999. Scientific expertise and political accountability: paradoxes of science in politics. *Sci. Public Policy* 26, 151–161. https://doi.org/10.3152/147154399781782437

Weitzman, M.L., 2009. On Modeling and Interpreting the Economics of Catastrophic Climate Change. Rev. Econ. Stat. 91, 1–19. https://doi.org/10.1162/rest.91.1.1

Weitzman, M.L., 2003. *Income, Wealth, and the Maximum Principle*. Harvard University Press, Cambridge, MA, USA.

Weitzman, M.L., 1976. On the Welfare Significance of National Product in a Dynamic Economy. *Q. J. Econ.* 90, 156–162. https://doi.org/10.2307/1886092

West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., Horowitz, L.W., Lamarque, J.-F., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nat. Clim. Change* 3, 885–889. https://doi.org/10.1038/nclimate2009

2 Beyond the 2°C limit: Facing the economic and institutional challenges

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Abstract

With very high risk of severe, widespread and irreversible impacts globally due to unabated anthropogenic climate change, we argue in this chapter that the 2°C limit can be justified by the synthesis of available scientific evidence as an application of the precautionary principle. In principle, the risks of mitigation differ fundamentally from the risks of climate change in terms of their nature, timescale, magnitude and persistence. Humankind has the technological means to solve the problem. However, the challenges of stringent mitigation action are enormous and have been increasing over the last decade because of the ongoing renaissance of coal, which does not allow for a decoupling of economic and population growth from emissions. Keeping a greater than 66% probability of staying below the 2°C limit, for example, would require current emission levels to be reduced by 40-70% by 2050, and emission levels of zero and below by the end of the 21st century. This requires a large-scale transformation in the way we produce and use energy, as well as how we use land. The most fundamental challenges are the oversupply of fossil fuels and the risks associated with negative emissions technologies, or high bioenergy deployment. A further delay in mitigation action substantially increases the difficulty of, and narrows the options for, this transformation.

Delays are associated with a growing dependence on negative emissions technologies as well as higher mitigation costs in the long run. In the near term, a fundamental departure from the business-as-usual development is required. Therefore, triggering short-term climate policy action is instrumental for any reasonable long-term climate goal. While the institutional challenges are tantamount, there are multiple rationales for pricing carbon and introducing complementary policies.

2.1 Dangerous climate change – the rationale of the 2°C limit

Faced with an increasing likelihood of "very high risk of severe, widespread and irreversible impacts globally" due to unabated anthropogenic climate change (IPCC 2014c), decision makers from all countries will meet at the 21st Conference of Parties (COP21) in Paris to work on a new international climate treaty. Climate policy is locked in a race against time, with greenhouse gas (GHG) emissions growing faster in the first decade of this century than in previous decades, despite a growing number of mitigation efforts. One of the most important drivers is the ongoing renaissance of coal, which does not allow for a decoupling of economic and population growth from GHG emissions (IPCC 2014a, Steckel et al. 2015). The oversupply of fossil fuels is one of the most fundamental challenges of climate policy. Understanding the technological and economic implications of limiting the disposal space of GHGs in the atmosphere (see Section 2) and triggering short-term mitigation action (see Section 3) is key to a workable and effective climate regime.

As highlighted in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the global mean temperature increase is an almost linear function of the cumulative release of CO_2 emissions to the atmosphere (see Figures SPM.10 and 12.45 in IPCC 2013; and Figure SPM.10 in IPCC 2014d). As carbon emissions accumulate in the atmosphere, the long-term temperature increase is determined in an irreversible way, unless technologies are available that allow for the net removal of carbon from the atmosphere, so-called 'negative emissions technologies'. While these may be necessary and useful within a portfolio of mitigation options, the required large-scale deployment of such technologies is associated with important risks (see Section 2) and is not able to prevent climate change within a reasonable time frame (IPCC 2013). These and other mitigation risks need to be weighed against the risks of climate impacts when determining a climate goal.

Economists have frequently tried to estimate the optimal balance between mitigation, adaptation and residual climate impacts. However, the underlying differences in methodological approaches and important gaps in knowledge make it challenging to carry out direct comparisons of these impacts in the form of cost-benefit calculations (Kunreuther et al. 2013, IPCC 2014e). More fundamentally, the identification of an optimal climate goal is based on many implicit value judgements and ethical considerations, which may be contested in pluralistic societies. Such judgements and considerations are fundamentally important, for example, when the damages from climate change, which are mainly incurred by future generations, are counted against the costs of mitigation, which are largely borne by today's generations (Kolstad et al. 2014). It therefore seems appropriate to take a risk management perspective that evaluates the risks of climate change (in terms of impacts and adaptation limits) and the risks of mitigation action (in terms of mitigation costs and potential adverse side-effects of mitigation technologies). This ultimately leaves the decision about the most desirable temperature level to policymakers and the public, who may base their discussions on the range of different risks, information about which is provided in the AR5 (Edenhofer and Kowarsch 2015).

Increasing temperatures raise the likelihood of severe, widespread and irreversible impacts (IPCC 2014c). Without additional mitigation efforts, the global mean temperature will increase by about 4°C (3.7-4.8°C based on the median climate response) by the end of the 21st century and will lead to high to very high climate change risks even with adaptation (Clarke et al. 2014, IPCC 2014a, IPCC 2014e). These include inter alia the loss of the Arctic ice sheet, substantial species extinctions, consequential constraints for human activities and global and regional food insecurity (IPCC 2014c). Limiting warming to below 2°C would reduce these risks of climate change substantially compared to business as usual, particularly in the second half of the 21st century (IPCC 2014c, IPCC 2014d). The large differences in risk between a 4°C and a 2°C world were therefore clearly emphasized in the AR5, whilst the difficulties in understanding the differential climate impacts for small temperature changes – such as 1.5°C, 2°C, 2.5°C or 3°C – were also acknowledged. Even a temperature increase of 2°C and below is associated with some risks from climate damages irrespective of mitigation and adaptation efforts (IPCC 2014d).

In contrast to climate damages, the risks of mitigation are generally not irreversible (except, for example, nuclear accidents and biodiversity loss) because they allow for trial and error and therefore for a social learning process in climate policy implementation. Mitigation risks are thus seen as differing fundamentally from the risks of unabated climate change in terms of their "nature, timescale, magnitude and persistence" (IPCC 2014e). Mitigation risks, however, also differ across alternative mitigation pathways.[4] These differences mainly depend on the availability and choice of technologies as well as the stringency and timing of GHG emissions reductions (see Section 3) (Clarke et al. 2014, IPCC 2014a).

Once a certain temperature level has been exceeded, only two options remain to deal with climate change: adaptation and solar radiation management (SRM), the latter of which tries to intentionally modify the earth's radiative budget. Some environmental impacts of climate change, such as ocean acidification, cannot be addressed by SRM technologies. There may also be other adverse side-effects that need careful assessment (IPCC 2013). Given the inherent uncertainties of the impacts of these options and the future impacts of climate change, aiming for the 2°C limit can thus be seen as an application of the precautionary principle, which emerges from the synthesis of scientific evidence and the value judgements by experts of how to avoid dangerous climate change. Whilst the global mean temperature cannot be controlled directly, a carbon budget can be defined which allows the limitation of the global mean temperature with a specific probability (see Table SPM.1 in IPCC 2014b). However, the window of opportunity to stay below the 2°C limit is rapidly closing, as the next section shows.

[4] Many mitigation technologies also entail co-benefits for non-climate policy objectives (von Stechow et al. 2015). These often accrue locally and may provide incentives for unilateral mitigation action; they are discussed in Section 3.3.

2.2 Technological and economic implications of the 2°C limit

Limiting climate risks by keeping global mean temperature increase below 2°C (with a greater than 66% probability) implies a remaining carbon budget of about 1,000 (750-1,400) $GtCO_2$ (IPCC 2014e). If current trends continue, this budget will be completely used up within the next 20-30 years. With more than 15,000 $GtCO_2$ in fossil fuel reserves and resources in the ground, it is clear that we will not run out of fossil fuels. Rather, it is the limited disposal space for waste GHGs of the atmosphere that constitutes the ultimate scarcity of the 21st century (see Figure 2.1). Staying within this tight carbon budget implies that annual GHG emissions would need to be reduced by 40-70% by 2050 and decline towards zero and below thereafter. This requires rapid improvements in energy efficiency and a 3-4-fold increase in the share of zero- and low-carbon energy supply from renewables, nuclear energy and carbon dioxide capture and storage (CCS), or bioenergy with CCS (BECCS) by 2050 (Clarke et al. 2014).

The majority of scenarios with a greater than 66% probability of keeping average global temperature rise below 2°C can only stay within the carbon budget if the carbon debt is repaid through global net negative emissions towards the end of the 21st century. In other words, more CO_2 would need to be removed from the atmosphere through large-scale deployment of negative emission technologies, such as BECCS or afforestation, than is released by all human activities. These challenges can be alleviated to some extent through reductions in final energy demand in the near term, decreasing the amount of fossil fuels used and thus reducing the immediate pressure for decarbonising energy supply. This would also entail co-benefits that outweigh the few adverse side-effects of mitigation action in the transport, buildings, and industry sectors. On the energy supply side, the balance depends to a larger extent on the specific technology and implementation context (Clarke et al. 2014, von Stechow et al. 2015).

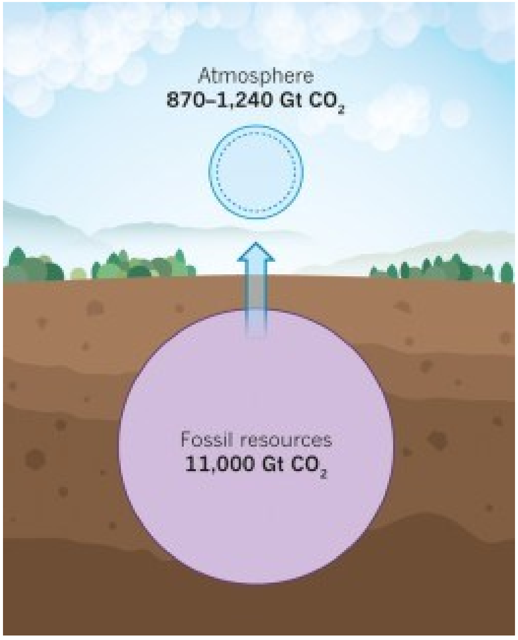


Figure 2.1 Fossil-fuel resources exceed the atmospheric disposal space for carbon emissions. Used with permission of Springer Nature, from Jakob and Hilaire (2015a) Unburnable fossil-fuel reserves. *Nature* 517, 150–151.

In addition to these technological challenges, staying within the remaining carbon budget would also imply a devaluation of coal, oil and gas assets.[5] Compared to business as usual, over 80% of coal reserves would need to remain underground as well as a third of oil and half of gas reserves (McGlade and Ekins 2015). This effect can be buffered to some extent by the deployment of BECCS, which has the potential to remove some of the emissions from the additional combustion of fossil fuels. If CCS is not available, however, this flexibility would be removed, calling for immediate GHG emissions reductions. This would have important implications for the allowed extraction rates and the above numbers would increase to 89%, 63% and 64%, respectively (Bauer et al. 2016, Jakob and Hilaire 2015).

One critical constraint on BECCS deployment is the large-scale availability of various bioenergy feedstocks (see Tavoni et al. 2013). Deployment levels of total (modern) bioenergy in 2°C scenarios without delay and limits to technological availability are in the range of 10-245 EJ/yr by 2050 and 105-325 EJ/yr in 2100, increasing the share of bioenergy in total primary energy from 35% in 2050 to as much as 50% in 2100 (Creutzig et al. 2014, Smith et al. 2014). Whether or not these amounts of bioenergy can be supplied in a sustainable manner is highly contested, with some experts emphasising the large mitigation potential of bioenergy and others highlighting the risks associated with such high bioenergy deployment levels (Creutzig et al. 2012a, 2012b). The main adverse side-effects discussed relate to possible reductions of land carbon stocks, as well as negative impacts on ecosystems, biodiversity, food security and livelihoods. The sustainable technical bioenergy potential is estimated to be around 100 EJ/yr in 2050, with high agreement in the literature, and up to 300 EJ/yr with medium agreement (Creutzig et al. 2014, Smith et al. 2014).

The technological challenges and adverse side-effects of staying below the 2°C limit increase further as stringent emissions reductions are delayed. This results from the faster timescales over which the required technologies need to be implemented. Figure 2.2 highlights that unless GHG emissions are reduced below current levels in 2030, the technological challenges of the 2°C limit increase substantially – particularly between 2030 and 2050 (Bertram et al. 2015, Riahi et al. 2015). Using a larger share of today's tight emissions budget also reduces the flexibility of technology choice, as staying below the temperature limit increasingly depends on the availability of potentially risky negative emissions technologies. Overall, the ability to hedge against the risks of mitigation across a broad technology portfolio becomes more and more constrained with increasing delays.

[5] By reducing the disposal space for waste GHGs in the atmosphere, climate policy not only reduces the resource rents of the owners of coal, oil and gas assets, but it also creates a 'climate rent'. These revenues from carbon pricing overcompensate the loss in resource rents (Bauer et al. 2013); they are discussed in more detail in Section 3.

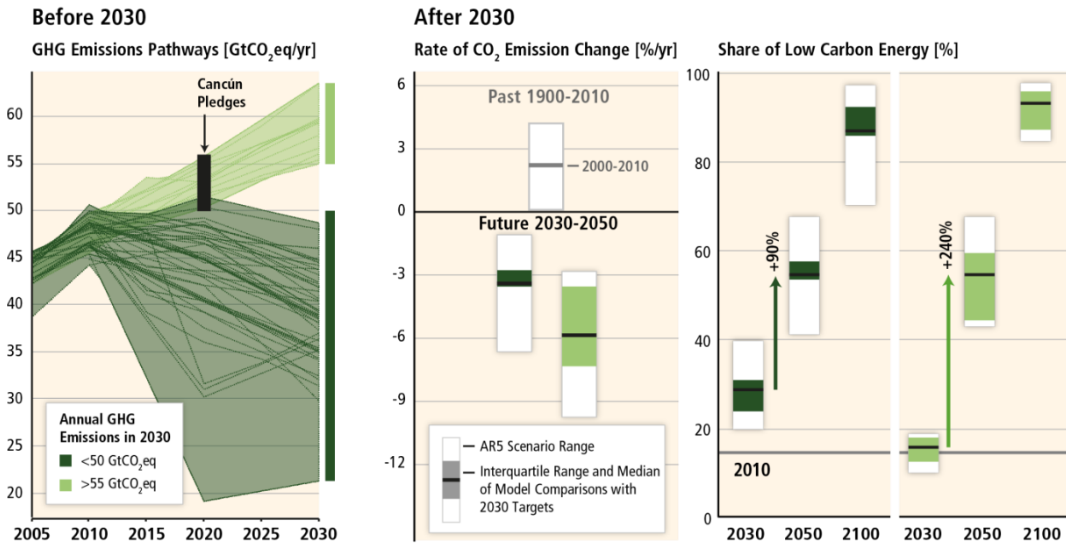
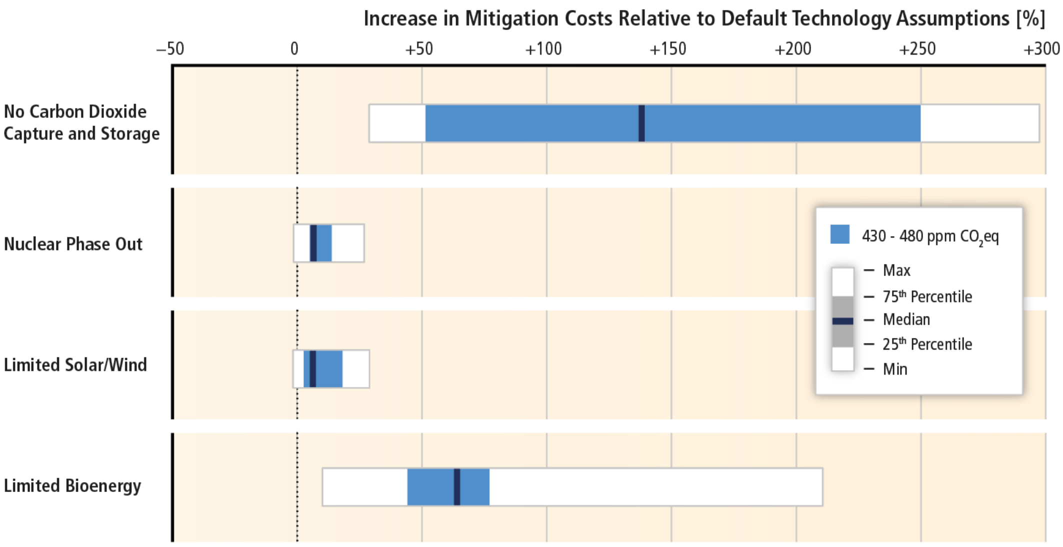


Figure 2.2 Increasing technological challenges associated with the energy system transformation in delayed relative to immediate mitigation scenarios consistent with staying below the 2°C limit with a roughly 50% probability. Notes: Technological challenges are represented in terms of the average annual rate of carbon emissions reductions (2030-2050, middle panel) and low-carbon energy upscaling (2030-2050/2100, right panel). Left panel shows GHG emission pathways between 2005 and 2030. Compared to immediate mitigation scenarios (dark green, GHG emissions <50 Gt CO_2-equivalent in 2030), delayed mitigation scenarios (light green, GHG emissions >55 Gt CO_2-equivalent) are characterized by much faster emissions reductions and much faster upscaling of low-carbon energy technologies between 2030 and 2050. The black bar shows the uncertainty range of GHG emissions implied by the Cancún Pledges. For more details, see IPCC (2014b).

Mitigation costs increase with growing mitigation ambition but are characterised by large uncertainties. Staying below the 2°C limit with a greater than 66% probability would imply reducing global consumption levels relative to business as usual by 5% (3%-11%) by 2100. Staying below a 2.5°C and 3°C limit would imply decreasing consumption levels by 4% (1%-7%) and 2% (1%-4%), respectively. For comparison, business-as-usual consumption itself grows between 300% to more than 900% over this period (IPCC 2014a). While these reductions in consumption levels are by no means negligible, they seem comparatively moderate. They also hinge on the assumption of effective global institutions and the establishment of a global, uniform carbon price.

Limiting the availability of key mitigation technologies such as CCS and bioenergy might reduce some of the adverse side-effects of these technologies but would increase discounted mitigation costs by approximately 140% (30-300%) and 60% (40-80%) by the end of the century, respectively (Figure 2.3). Delaying emissions reductions further increases the costs of reaching specific climate goals. A delay would protect the rents of fossil fuel owners, today's cost savings would thus be eclipsed by future cost increases. For example, delaying stringent mitigation through 2030 could raise the aggregate costs of mitigation by 30-40% (2-80%) by 2050 and by 15-40% (5-80%) by 2100 (in scenarios with a roughly 50% probability of staying below the 2°C limit) (Clarke et al. 2014).



Source: Based on Clarke et al. (2014)

Figure 2.3 The impacts of a limited mitigation technology portfolio on the relative increase in mitigation costs compared to a scenario with full availability of technologies in mitigation scenarios consistent with staying below the 2°C limit with a roughly 50% probability. Notes: The cumulative mitigation costs (2015-2100) are presented as net present value, discounted at 5% per year. Nuclear phase out = No addition of nuclear power plants beyond those under construction and existing plants operating until the end of their lifetime; Limited Solar / Wind = a maximum of 20 % of global annual electricity supply from solar and wind; Limited Bioenergy = a maximum of 100 EJ/yr modern bioenergy supply globally. For more details, see Clarke et al. (2014).

2.3 Triggering short-term mitigation action

A fundamental departure from business-as-usual development is required to leave the window of opportunity open to stay below the 2°C limit. Triggering short-term climate policy action is instrumental to achieving any reasonable long-term climate goal – short-term action reduces the risks of increasing future mitigation costs and the risks of relying on negative emissions technologies with potentially large adverse-side-effects.

As discussed by Sterner and Köhlin (2015) and Stavins (2015), the necessity for introducing a clear price signal through carbon taxes or emissions trading becomes evident when considering the required changes in the different sectors and looking at the required reallocation of investment flows. In the energy sector, for example, new investment strategies away from fossil fuel extraction and use towards energy efficiency and low-carbon technologies for energy generation are urgently needed (Figure 2.4). But despite its necessity, carbon pricing is perceived as extremely demanding. The feasibility of an optimal global carbon price is currently limited as free-rider incentives seem to undermine the willingness of parties to participate in an ambitious international climate agreement (Carraro 2014, Cramton et al. 2015). It is therefore even more remarkable that a number of countries – including the majority of the world's 20 largest emitters – have started implementing GHG emissions reduction policies on their own accord.

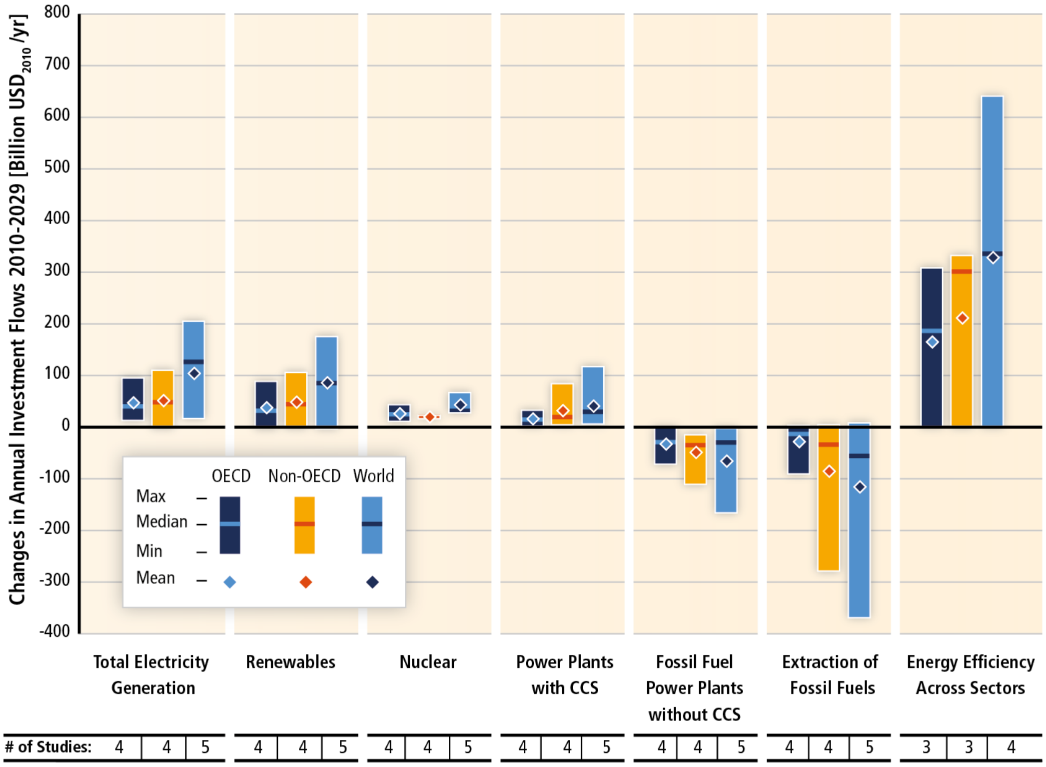


Figure 2.4 Change in annual energy sector investment flows towards low-carbon energy technologies in mitigation scenarios consistent with staying below the 2°C limit with a roughly 50% probability relative to the average business-as-usual level (2010–2029). Notes: Results are based on a limited number of model studies and model comparisons (numbers in the bottom row) highlighting that investment needs are an evolving area of research. The extent to which the investment needs in one region translate into regional mitigation costs depends on the effort-sharing regime, which has important effects on the relative cost burden (Tavoni et al. 2013, Höhne et al. 2014). For more details, see Gupta et al. (2014).

Several unilateral and often short-term incentives for introducing climate policies and establishing GHG emissions pricing schemes exist: i) the efficient generation of additional revenues for government budgets; ii) the use of carbon-pricing revenues for the provision of public goods or infrastructure investments in welfare-enhancing ways; iii) the introduction of Pigouvian carbon pricing to internalize national climate impacts; and iv) the realization of co-benefits from GHG emissions reductions (Edenhofer et al. 2015). Interestingly, all of these unilateral incentives for domestic carbon prices are particularly relevant for developing countries.

1. Carbon pricing helps to broaden the often-thin tax base in countries with large informal sectors (Bento and Jacobsen 2007, Bento et al. 2013, Markandya et al. 2013). With the possibility to recycle these additional carbon price revenues, potentially regressive effects may be compensated and/or existing distortionary taxes (that particularly affect low-income groups) may be reduced. Carbon pricing can therefore enhance economic growth without adverse distributive effects (Casillas and Kammen 2010, Goulder 2013, Somanathan et al. 2014). As a recent IMF report shows, however, one ton of carbon emissions receives, on average, more than 150 US$ in subsidies. The removal of all such subsidies, accompanied by an appropriate price on carbon, would benefit especially developing countries (Coady et al. 2015).

2. Carbon-pricing revenues could reduce the large investment gap in public infrastructure that provides access to basic needs, such as universal access to water, sanitation, and clean energy (Edenhofer et al. 2015). For example, the investment needs for energy efficiency and low-carbon technologies (see Figure 2.4), universal energy and water access and sanitation access in non-OECD countries are well within expected revenues from climate policy (Hutton 2012, Pachauri et al. 2013, Jakob et al. 2015a). It is worth noting that the removal of fossil fuel subsidies also has a remarkable potential to raise revenues. If these subsidies of approximately US$550 billion were to be redirected to investments in basic infrastructure over the next 15 years, substantial improvements could be made in reducing poverty. This includes universal access to clean water in about 70 countries, improved sanitation in about 60 countries, and access to electricity in about 50 countries (out of roughly 80 countries that do not yet have universal access). Such investments would also increase the long-term growth prospects of poor economies (Jakob et al. 2015b). Additionally, the removal of these subsidies would cut global carbon emissions by more than 20%, and reduce pre-mature deaths related to air pollution by more than half (Coady et al. 2015).
3. A substantial share of optimal carbon prices (with maximum values of 10-40%) could internalize the expected domestic damages from climate change in developing regions (Figure 3 in Edenhofer et al. 2015).
4. Co-benefits, for example those related to reducing the health and environmental externalities from currently high air pollution, further increase the incentives to trigger short-term mitigation action in developing countries (Nemet et al. 2010, West et al. 2013).

Most of the aforementioned unilateral incentives to introduce climate policies are also particularly relevant for industrialized countries. The introduction of a carbon price provides the flexibility to reduce existing distortionary taxes and thus increase the overall efficiency of the economy. In addition, a tax on fixed production factors such as fossil fuels could stimulate the redirection of investments towards producible capital (Edenhofer et al. 2015). The revenues from carbon pricing could also provide ample funds for the investments required in the energy sector (see Figure 2.4), or for addressing investments needs in the transport sector and existing market failures in technology R&D. Finally, revenues may be used for financing adaptation needs resulting from the unavoidable impacts from climate change (Malik and Smith 2012), which may range between US$25-100 billion per year by 2015-2030 (Fankhauser 2010).

These unilateral incentives show that finance ministers might be interested in carbon pricing even though they are not primarily interested in emissions reductions (Franks et al. 2014). Still, mitigation efforts that are purely motivated by national interests are not expected to achieve the globally optimal carbon price. They could nonetheless contribute towards closing the ‘emission price gap’, i.e. the difference between the level of current GHG prices and a globally optimal carbon price (see Figure 2.5). The crucial question remaining is to what extent unilateral action by some countries, regions or industries can promote collective action and can facilitate cooperation on the international level (Ostrom 2010, Urpelainen 2013, Cramton et al. 2015).

It has been shown above that the prospects of carbon pricing are less bleak when the investment gap in public infrastructure is financed by carbon-pricing revenues, co-benefits can be realized, and the removal of distortionary taxes is taken into account. This will not lead automatically to international cooperation and to a global carbon price. However, should domestic carbon pricing no longer be perceived as committing political suicide, the remaining carbon price gap will be easier to close by international agreements. Admittedly, the challenge of international cooperation remains and innovative proposals are needed to solve this globally pressing problem (e.g. Cramton et al. 2015, Barrett and Dannenberg 2012, Stewart et al. 2015, Keohane and Victor 2015, Stavins 2015). However, the potential for domestic carbon pricing as a short-term entry point to a longer-term solution has been widely underestimated. It would open up new perspectives for tackling the climate problem if finance ministers were to become much closer allies of environmental ministers, working together to close the emission price gap and thus triggering short-term mitigation action.

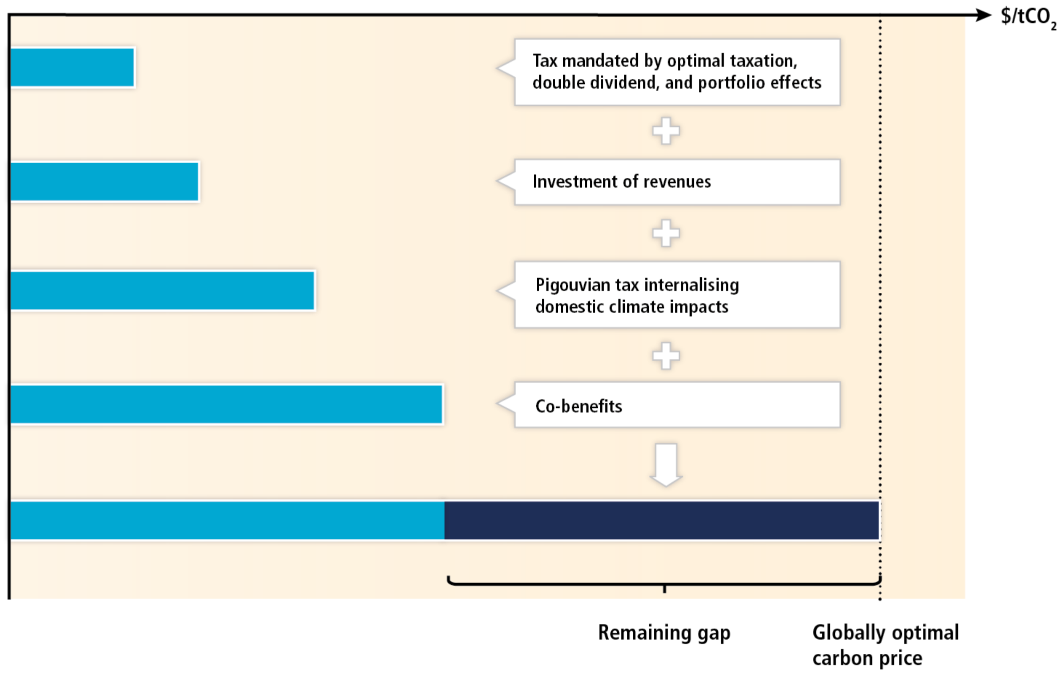


Figure 2.5 Incentives for unilateral introduction of carbon prices and their role in closing the emission price gap. Used with permission of Elsevier, from Edenhofer et al. (2015) Closing the emission price gap. *Glob. Environ. Change* 31(0), 132–143.

2.4 References

Barrett, S. and A. Dannenberg (2012), "Climate negotiations under scientific uncertainty", *Proceedings of the National Academy of Sciences* 109(43): 17372–17376.

Bauer, N., I. Mouratiadou, G. Luderer, L. Baumstark, R. Brecha, O. Edenhofer and E. Kriegler (2016), "Global fossil energy markets and climate change mitigation – an analysis with REMIND", *Climatic Change* 136: 69–82.

Bento, A. M. and M. Jacobsen (2007), "Ricardian rents, environmental policy and the "double-dividend" hypothesis", *Journal of Environmental Economics and Management* 53(1): 17–31.

Bento, A. M., M. R. Jacobsen and A. A. Liu (2013), "Environmental Policy in the Presence of an Informal Sector" (available at http://works.bepress.com/antonio_bento/25).

Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac and J. Eom (2015), "Carbon lock-in through capital stock inertia associated with weak near-term climate policies", *Technological Forecasting and Social Change* 90, Part A: 62–72.

Carraro, C. (2014), "International Environmental Cooperation", in *Handbook of Sustainable Development*, Cheltenham, UK: Edward Elgar Publishing.

Casillas, C. E. and D. M. Kammen (2010), "The Energy-Poverty-Climate Nexus", *Science* 330(6008): 1181–1182.

Clarke, L., K. Jiang et al. (2014), "Assessing transformation pathways", in: Climate Change 2014: *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge, UK and New York: Cambridge University Press.

Coady D., I. Parry, L. Sears and B. Shang (2015), "How Large Are Global Energy Subsidies?", IMF Working Paper No. 15/105, Washington, DC.

Cramton, P., A. Ockenfels and S. Stoft (2015), "An international carbon price commitment promotes cooperation", in *EEEP Symposium: International Climate Negotiations*, Cleveland, OH: International Association for Energy Economics.

Creutzig, F., A. Popp, R. Plevin, G. Luderer, J. Minx and O. Edenhofer (2012a), "Reconciling top-down and bottom-up modelling on future bioenergy deployment", *Nature Climate Change* 2(5): 320–327.

Creutzig, F., C. von Stechow, D. Klein, C. Hunsberger, N. Bauer, A. Popp and O. Edenhofer (2012b), "Can Bioenergy Assessments Deliver?", *Economics of Energy & Environmental Policy* 1(2): 65–82.

Creutzig, F, N. H. Ravindranath, G. Berndes, S. Bolwig, R. Bright et al. (2014), "Bioenergy and climate change mitigation: an assessment", *GCB Bioenergy* 7(5): 916–944.

Edenhofer, O. and M. Kowarsch (2015), "Cartography of pathways: A new model for environmental policy assessments", *Environmental Science & Policy* 51: 56–64.

Edenhofer, O., M. Jakob, F. Creutzig, C. Flachsland, S. Fuss, M. Kowarsch, K. Lessmann, L. Mattauch, J. Siegmeier and J. C. Steckel (2015), "Closing the emission price gap", *Global Environmental Change* 31(0): 132–143.

Fankhauser, S. (2010), "The costs of adaptation", Wiley Interdisciplinary Reviews: Climate Change 1(1): 23–30.

Franks, M., O. Edenhofer and K. Lessman. "Why Finance Ministers Favor Carbon Taxes, Even if They Do Not Take Climate Change into Account", Discussion Paper No. 2015-67, Harvard Project on Climate Agreements, Belfer Center for Science and International Affairs.

Goulder, L. H. (2013), “Climate change policy’s interactions with the tax system”, *Energy Economics* 40, Supplement 1(0): S3–S11.

Gupta, S., J. Harnisch et al. (2014), “Cross-cutting Investment and Finance Issues”, in: *Climate Change 2014: Mitigation of Climate Change*. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge, UK and New York: Cambridge University Press.

Höhne, N., M. G. J. den Elzen and D. Escalante (2014), “Regional GHG reduction targets based on effort sharing: a comparison of studies”, *Climate Policy* 14: 122–147.

Hutton, G. (2012), “Global Costs and Benefits of Drinking-Water Supply and Sanitation Interventions to Reach the MDG Target and Universal Coverage”, World Health Organization, Geneva.

IPCC (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds)], Cambridge, UK and New York: Cambridge University Press.

IPCC (2014a), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge, UK and New York: Cambridge University Press.

IPCC (2014b), “Summary for Policymakers”, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds)], Cambridge, UK and New York: Cambridge University Press.

IPCC (2014c), “Summary for policymakers”, in: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds)], Cambridge, UK and New York: Cambridge University Press.

IPCC (2014d), “Summary for policymakers”, in: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

IPCC (2014e), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

Jakob, M. and J. Hilaire (2015b), “Using importers’ windfall savings from oil subsidy reform to enhance international cooperation on climate policies”, *Climatic Change* 131(4): 465–472.

Jakob, M., C. Chen, S. Fuss, A. Marxen, N. Rao and O. Edenhofer (2015a), "Using carbon pricing revenues to finance infrastructure access", paper presented at the European Association of Environmental and Resource Economists 21st Annual Conference, Helsinki, 24-27 June.

Jakob, M., C. Chen, S. Fuss, A. Marxen and O. Edenhofer (2015b), "Development incentives for fossil fuel subsidy reform", *Nature Climate Change* 5:709–712.

Keohane, R. O. and D. G. Victor (2015), "After the failure of top-down mandates: The role of experimental governance in climate change policy", in: Barrett, S., Carraro, C., de Melo, J. (Eds.), *Towards a Workable and Effective Climate Regime*. CEPR Press, London, pp. 201–12. https://cepr.org/chapters/after-failure-top-down-mandates-role-experimental-governance-climate-change-policy

Kolstad, C., K. Urama et al. (2014), "Social, Economic and Ethical Concepts and Methods", in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds)], Cambridge, UK and New York: Cambridge University Press.

Kunreuther, H., G. Heal, M. Allen, O. Edenhofer, C. B. Field and G. Yohe (2013), "Risk management and climate change", *Nature Climate Change* 3(5): 447-450.

Malik, A. S. and S. C. Smith (2012), "Adaptation to climate change in low-income countries: lessons from current research and needs from future research", *Climate Change Economics* 03(02): 1250005.

Markandya, A., M. González-Eguino and M. Escapa (2013), "From shadow to green: Linking environmental fiscal reforms and the informal economy", *Energy Economics* 40, Supplement 1(0): S108–S118.

McGlade, C., P. Ekins (2015), "The geographical distribution of fossil fuels unused when limiting global warming to 2°C", *Nature* 517: 187–190.

Nemet, G. F., T. Holloway and P. Meier (2010), "Implications of incorporating air quality co-benefits into climate change policymaking", *Environmental Research Letters* 5(1): 014007.

Oppenheimer M., B. Rudyk and R. Stewart (2015), "A building blocks strategy for global climate change", in: Barrett, S., Carraro, C., de Melo, J. (Eds.), *Towards a Workable and Effective Climate Regime*. CEPR Press, London, pp. 213–22. https://cepr.org/chapters/building-blocks-strategy-global-climate-change

Ostrom, E. (2010), "Polycentric systems for coping with collective action and global environmental change", *Global Environmental Change* 20(4): 550-557.

Pachauri, S, B. J. van Ruijven, Y. Nagai, K. Riahi, D. P. van Vuuren, A. Brew-Hammond and N. Nakicenovic (2013), "Pathways to achieve universal household access to modern energy by 2030", *Environmental Research Letters* 8(2): 024015.

Riahi, K., N. Kriegler, C. Johnson, C. Bertram, M. den Elzen et al. (2015), "Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals", *Technological Forecasting and Social Change* 90, Part A: 8–23.

Smith, P., M. Bustamante et al. (2014), "Agriculture, Forestry and Other Land Use (AFOLU)", in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds)], Cambridge, UK and New York: Cambridge University Press.

Somanathan, E., T. Sterner, T. Sugiyama et al. (2014), "National and Sub-national Policies and Institutions", in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds)], Cambridge, UK and New York: Cambridge University Press.

Stavins, R. N. (2015), "Linkage of regional, national, and sub-national policies in a future international climate agreement", in: Barrett, S., Carraro, C., de Melo, J. (Eds.), *Towards a Workable and Effective Climate Regime*. CEPR Press, London, pp. 283–95. https://cepr.org/chapters/linkage-regional-national-and-sub-national-policies-future-international-climate-agreement

von Stechow, C., D. McCollum, K. Riahi, J. C. Minx, E. Kriegler, D. P. van Vuuren, J. Jewell, C. Robledo-Abad, E. Hertwich, M. Tavoni, S. Mirasgedis, O. Lah, J. Roy, Y. Mulugetta, N. K. Dubash, J. Bollen, D. Ürge-Vorsatz and O. Edenhofer (2015), "Integrating global climate change mitigation goals with other sustainability objectives: A synthesis", *Annual Review of Environment and Resources* 40: 363–394.

Steckel, J. C., O. Edenhofer and M. Jakob (2015), "Drivers for the renaissance of coal", *Proceedings of the National Academy of Sciences* 112(29): E3775-E3781.

Sterner, T., G. Köhlin (2015), "Pricing carbon: The challenges", in: Barrett, S., Carraro, C., de Melo, J. (Eds.), *Towards a Workable and Effective Climate Regime*. CEPR Press, London, pp. 251–65. https://cepr.org/chapters/pricing-carbon-challenges

Tavoni, M. Kriegler, E., Aboumahboub, T., Clavin, K., de Maere, G. et al. (2013), "The distribution of the major economies' effort in the Durban platform scenarios", *Climate Change Economics* 4(4): 1340009

Urpelainen, J. (2013), "A model of dynamic climate governance: dream big, win small", *International Environmental Agreements: Politics, Law and Economics* 13(2): 107–125.

West, J. J., S. J. Smith, R. A. Silva, V. Naik, Y. Zhang, Z. Adelman, M. M. Fry, S. Anenberg, L. W. Horowitz, and J.-F. Lamarque (2013), "Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health", *Nature Climate Change* 3(10): 885–889.

3 Can bioenergy assessments deliver?

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Abstract

The role of biomass as a primary energy resource is highly debated. Next generation biofuels are suggested to be associated with low specific greenhouse gas emissions. But land consumption, demand for scarce water, competition with food production and harmful indirect land-use effects put a question mark over the beneficial effects of bioenergy deployment. In this chapter, we investigate the current state of bioenergy assessments and scrutinize the topics and perspectives explored in the Special Report on Renewable Energy Sources and Climate Change. We suggest that an appropriate assessment requires a comprehensive literature review, the explicit exposition of disparate viewpoints, and exploration of policy-relevant content based on plausible "storylines". We illustrate these storylines with the IPCC's emission scenarios and point routes to improve assessment making on the future role of bioenergy.

Keywords

Bioenergy, Assessment, Tradeoffs, Sustainability, Scenarios

3.1 Introduction

Bioenergy plays a crucial role in the global transition from fossil fuels to renewable energy, and possibly also for climate change mitigation. With intensive use of traditional biomass, primary energy from plant resources currently exceeds that of other renewable options, including wind energy. The benefits and impacts of bioenergy depend on what feedstocks are used for what purpose and how and where they are produced. In particular, greenhouse gas (GHG) emissions from bioenergy use are widely varying, uncertain and the subject of intensive debates (e.g., Malca and Freire 2010; Plevin et al. 2010; Creutzig et al. 2012). One part of the scientific literature indicates that high direct and indirect land-use emissions compromise the benefits of the current use of many biofuels (e.g., Crutzen et al. 2008; Hertel et al. 2009; Popp et al. 2011a). Another part of the literature highlights the potential of large-scale bioenergy deployment to mitigate climate change and to even produce negative GHG emissions in combination with carbon capture and storage technologies (e.g., Edenhofer et al. 2010). In addition to the climate conundrum, large-scale deployment of bioenergy is influenced by energy security concerns, is subject to industry interests, and impacts food security, biodiversity, water scarcity, soil quality and subsistence farming (e.g., Fargione et al. 2010).

The complexity of this system produces a high level of uncertainty about future outcomes. Policy makers therefore have a need for comprehensive analysis to help inform their decisions about energy, climate change and associated risks. Taking climate change mitigation as a mitigation potential of bioenergy deployment in various scenarios? And: how sustainable is bioenergy deployment in these scenarios? Only a comprehensive and balanced assessment, integrating analyses from diverse research communities, can provide at least tentative answers to these questions and identify the main sources of uncertainty. Such an assessment is crucial to inform political decisions that intend to influence the future portfolio of mitigation options. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) aims to provide such an assessment for renewable energies in general (IPCC 2011a), and bioenergy in particular (Chum et al. 2011). Here we critically evaluate this assessment based on the understanding that the mitigation perspective needs to be accompanied by other perspectives to avoid a one-dimensional analysis. Section 3.2 outlines the tasks of an assessment. Section 3.3 reviews the insights from the SRREN on bioenergy. Section 3.4 scrutinizes the representation of bioenergy in the different SRREN chapters based on the assessment requirements. Section 3.5 suggests possible routes towards improved assessment making.

3.2 How to carry out assessments

Assessments are emerging as a distinct literature category in academia (Keller 2010). Prominent examples include the assessment reports of the IPCC (2007), the upcoming Global Energy Assessment and Global Environmental Outlook, the Millennium Ecosystem Assessment (MA, 2005), and more specific reports such as the Assessment Report of the Urban Climate Change Research Network (Rosenzweig et al. 2011), and many assessments in other areas of science. Unlike scientific publications, assessment reports are requested by a legal body and subject to specific criteria and procedures, like the review process, to ensure high quality. Assessment preparation can take up to five years including scoping, author selection and several iterations of writing and reviewing.

The IPCC reports are special in that they result from an official UN process, signed off by all 194 national governments that are members of the IPCC. The focus of the current literature on assessment making has primarily been on the underlying model of scientific policy advice (e.g., Pielke 2007; Beck 2010), on specific aspects of assessment making, such as the treatment and communication of uncertainty (e.g., van der Sluijs et al. 2008; Mastrandrea et al. 2011) or on the assessment process (e.g., Agrawala 1998; Farrell and Jäger 2006)—focusing on the impact of assessments (Cash et al. 2002; Mitchell et al. 2006; Keller 2010). We are, however, not aware of any framework that specifies criteria for evaluating the content of a particular assessment. For evaluation of an IPCC report, such as the SRREN, the procedures of the IPCC itself will thus provide us with a point of departure.

The IPCC states that "the best possible scientific and technical advice should be included so that the IPCC Reports represent the latest scientific, technical and socio-economic findings and are as comprehensive as possible"; and in preparing an IPCC report, "Lead Authors should clearly identify disparate views for which there is significant scientific or technical support" (IPCC 2011b, p. 6). Also: "It is important that reports describe different (possibly controversial) scientific, technical, and socio-economic views on a subject, particularly if they are relevant to the policy debate" (IPCC 2011b, p. 7).

Hence, an IPCC assessment needs to meet three tasks: 1) provide a comprehensive review of the relevant literature; 2) identify and possibly reconcile disparate views; and 3) present the scientific content in a manner relevant to policy makers, drawing on the outcomes of the first two tasks. Let us elucidate each task in turn.

First, the review character of an assessment is different from most review articles in disciplinary journals. A review article usually summarizes the results of a particular scientific community on a specific topic, e.g., land modelers on biomass resource potential. An assessment, in contrast, has the mandate to bring different epistemic communities together, communities that work on the same topic but contribute different methods, perspectives, languages, and assumptions.[6] As a consequence, an assessment needs to be comprehensive both in topics covered and in participation of epistemic communities.

Second, by bringing together different communities, an assessment allows for the identification of disparate views and perspectives and scrutiny of the reasons for divergence. In particular, an exploration of the whole solution space (e.g., identifying costs, benefits and risks of mitigation options) becomes challenging when the fact-value separability cannot be taken for granted as a precondition for the distinction between

[6] According to Haas, an epistemic community is "a network of professionals with recognised expertise and competence in a particular domain and an authoritative claim to policy relevant knowledge within that domain or issue-area" (Haas 1992, p. 3).

means and ends. The separation between facts and values collapses when indirect consequences of means have the potential to undermine the achievement of the societal ends that the means are intended to address (Dewey 1988). The relevant example here is where extensive use of bioenergy (the means) to achieve climate change mitigation (the end) causes unforeseen consequences (e.g., increased risk of famines) (Edenhofer and Seyboth 2013). Ideally, a communication effort between scientific communities helps to track down different assumptions and worldviews, to make value judgments transparent, and to explain the observed divergence in results and types of analysis. If this is achieved, it is much easier to reconcile divergent results and also identify possible co-benefits and trade-offs between societal goals and thus detect and possibly avoid unintended consequences and promote co-benefits. On this basis, assessments can often identify research gaps and opportunities for collaboration and can produce a closed loop by communicating these findings to the scientific community.

Third, an IPCC assessment is supposed to be policy-relevant without being policy-prescriptive. When results of different epistemic communities mismatch or when the different types of analysis are difficult to reconcile, the communication of the respective sets of assumptions and worldviews and their corresponding results become paramount. An assessment can then inherit the role of an “honest broker”, communicating the divergent scientific conclusions to policymakers in an accessible way (Pielke 2007). The use of “storylines” in assessments breaks down complexity and constitutes a useful tool for communication to policy makers, but also to peers and the interested public (Kriegler et al. 2010, Arnell et al. 2011). We understand a storyline to be a narrative (e.g., a rapidly globalizing and consumption-oriented world with efficient markets). Scenarios correspond to a storyline by specifying a particular set of assumptions (e.g., population and economic growth; energy poverty; increasing energy demand; technological development; lifestyle changes, such as a global increase in meat consumption). Given a specific scenario, models can then produce pathways, which provide numeric outcomes and impacts (e.g., bioenergy deployment). Comparison between scenario assumptions will then help to explain the discrepancy between different outcomes and the corresponding impacts. Varying perspectives of epistemic communities can translate into different storylines and corresponding scenarios, but also to different emphasis on dimensions within one storyline. Comparing different storylines with varying emphasis allows the identification and possibly quantification of risks, trade-offs and co-benefits. Feeding these results back into the sphere of public debate might result in substantial revisions of societal goals and the respective policy instruments.

3.3 State of bioenergy assessment

Before evaluating the SRREN bioenergy assessment, we need to summarize its main findings. We roughly follow the SRREN and discuss five key dimensions of the bioenergy assessment: 1) costs; 2) life-cycle emissions; 3) resource potential and deployment; 4) socioeconomic and environmental impacts; and 5) governance (sections 3.3.1–3.3.5). For this, we mostly rely on SRREN Chapter 2 (“Bioenergy”: Chum et al. 2011), Chapter 9

(“Renewable Energy in the Context of Sustainable Development”: Sathaye et al. 2011), Chapter 10 (“Mitigation Potential and Costs”: Fischedick et al. 2011), and Chapter 11 (“Policy, Financing and Implementation”: Mitchell et al. 2011).

3.3.1 Costs of bioenergy

The SRREN cost analysis is based on levelized cost of energy (LCOE) calculations. LCOE is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. As a result, levelized costs of energy enable an apple-to-apple comparison of different sources of energy with widely diverging cost structure. Figure 3.1 displays levelized costs of bioenergy for various feedstocks and purposes. Ethanol and biopower production show cost reductions due to technological learning comparable to those of other renewable energy technologies. But estimated feedstock cost supply curves also point out that increased production leads to higher marginal costs, e.g., because of lower quality land (Chum et al. 2011).

Crucially, the SRREN finds that levelized costs of bioenergy are already competitive with fossil fuels for some feedstocks, purposes and countries. For example, ethanol from sugarcane outperforms gasoline in the Brazilian transport market. In Europe, biomass heating applications in the building sector, often designed as cogeneration facilities, are cost competitive and increase rapidly. The large amount of traditional biomass, still dominating overall biomass use, is mostly grown locally, and is often not part of formal markets.

3.3.2 Life-cycle emissions

As bioenergy use is partially motivated by climate change, the carbon balance of feedstocks and production pathways is of particular interest and is frequently instrumentalized for policy goals (Creutzig & Kammen 2009). The SRREN breaks down life-cycle emissions according to the different life-cycle methods. Relying on attributional life-cycle analysis (LCA)—accounting for the direct emissions of the supply-use-disposal chain, the SRREN reveals that biomass used for electricity and heat always has lower CO_2 life-cycle emissions than fossil fuels (SRREN Fig. 2.10). For transportation, the relative performance of biofuels compared with gasoline and diesel depends on the particular feedstock and production context. Possibly more relevant, however, are the consequential marginal GHG emissions of bioenergy use, including e.g., the indirect land-use emissions from deforestation. SRREN Figure 2.13 summarizes emissions from land-use change, differentiating between models and world regions. The figure and the accompanying text demonstrate unambiguously that land-use emissions are potentially higher than the direct emissions of conventional fuels. A key challenge is that emissions occur up-front, contributing immediately to climate change, whereas potential carbon savings occur in the future, after paying back the initial carbon debt (Fargione et al. 2008). The SRREN concludes that increased bioenergy deployment needs to be supplemented with better protection of tropical forests and other carbon-rich ecosystems.

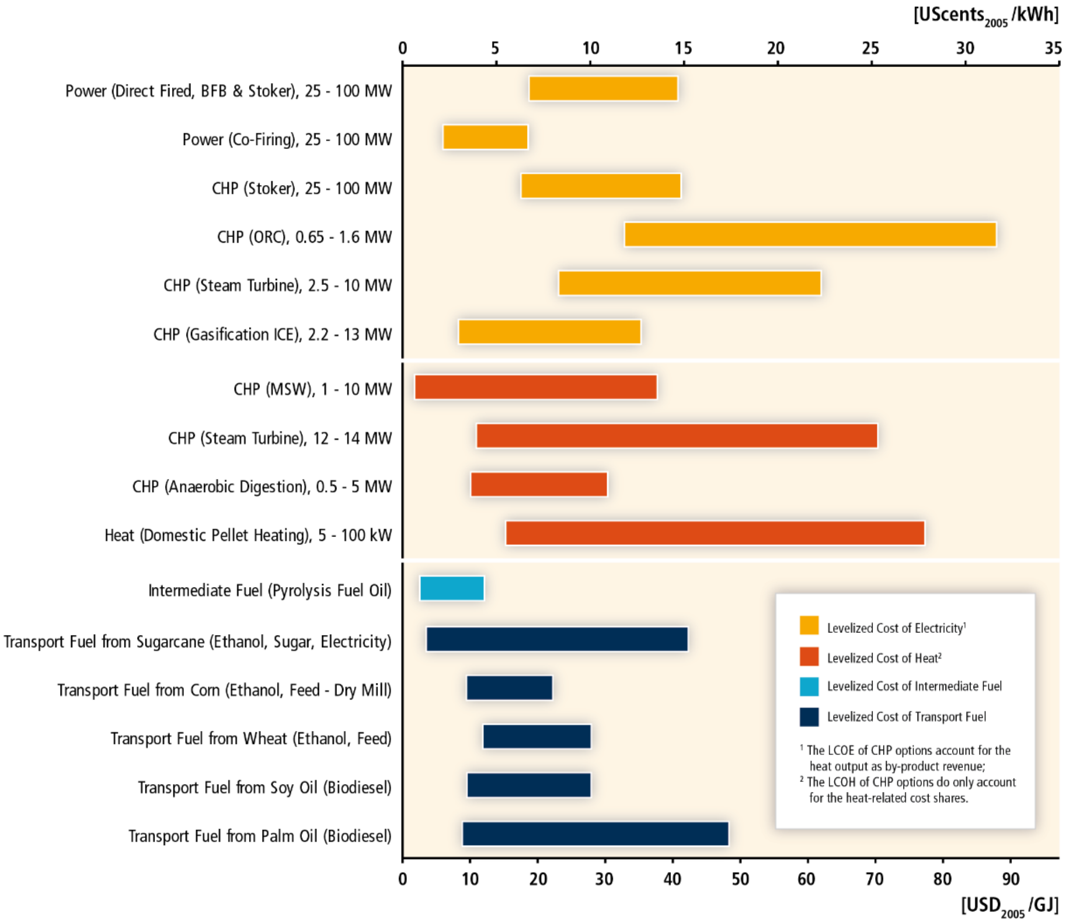

Figure 3.1 Levelized cost of energy service from commercially available bioenergy systems at a 7% discount rate and with feedstock cost ranges differing between technologies (from Chum et al. 2011, Fig. 2.18). For biofuels, the range of levelized costs represents production in a wide range of countries whereas levelized costs of electricity and heat are given only for major user markets of the technologies for which data were available. The underlying cost and performance assumptions used in the calculations are summarized in SRREN Annex III.

3.3.3 Resource Potential and Deployment

According to the literature review in the SRREN, the global technical potential for bioenergy, considering also demand for other land-use, ranges from less than 50 EJ to more than 1000 EJ in 2050 (Figure 3.2a; Dornburg et al. 2010; Haberl et al. 2010). In some of the studies, the theoretical potential is even considered to exceed 1500 EJ by 2050 (e.g., Smeets et al. 2007). Contrast this with current energy demand of around 500 EJ and expected energy demand of between 500 and 1000 EJ in 2050 (Fischedick et al. 2011). The huge uncertainty is rooted in the following factors, among others: soil degradation; water scarcity; yield growth; production potential of degraded land; nature protection; and climate change feedback.

Based on this review of the available literature, the authors conclude that realistic deployment levels of biomass for energy could reach a range of 100 to 300 EJ/yr around 2050 (Figure 3.2b). But: “the inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize” (Chum et al. 2011). Based on cost projections, including the opportunity cost of land, future biomass supply curves can be derived, implicitly determining the market potential (SRREN Figure 2.5).

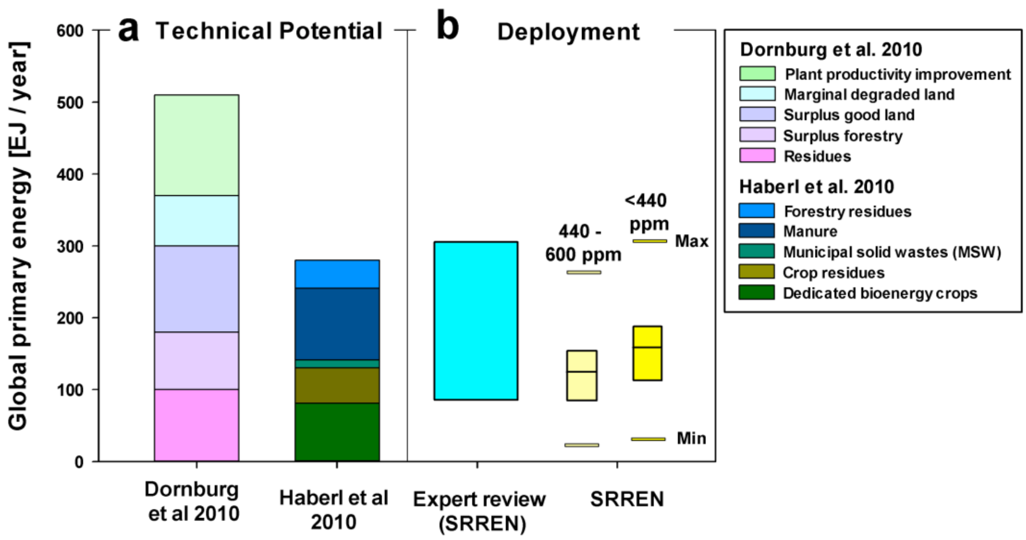

Figure 3.2 a) Bioenergy technical potential in 2050 listed according to categories. b) Expert judgment on deployment in 2050 from SRREN Chapter 2 and deployment scenarios from SRREN Chapter 10. Source: Used with permission of Springer Nature, adapted from Creutzig et al. (2012) [Reconciling top-down and bottom-up modelling on future bioenergy deployment](). *Nat. Clim. Change* 2(5), 320-327.

Different assumptions on economic and energy demand growth, the cost and availability of competing low-carbon technologies as well as different mitigation scenarios add complexity to potential estimates. Taking these into account, integrated assessment models (IAMs, see Box 3.1) obtain ranges of potential deployment of bioenergy comparable to the SRREN Chapter 2 expert judgment. In these models, deployment is estimated to be higher when mitigation targets are more ambitious (Figure 3.2b).

3.3.4 Socioeconomic and environmental impacts

In addition to the GHG performance of bioenergy options (see section 3.3.2), other socioeconomic and environmental impacts are also analyzed in the SRREN (Chum et al. 2011; Sathaye et al. 2011). First, the increased demand for agricultural inputs such as land and water influences food commodity prices and thus food security. The SRREN points out possibly relevant but uncertain contributions of increased biofuels production to the food price increase in the mid-2000s. This implies an overall adverse effect on food security in developing countries (World Bank 2009).

Second, increased biomass production may imply increased income for farmers and agrobusiness. But using productive and degraded lands for bioenergy purposes might compromise the needs of local populations for subsistence farming. This is particularly important for vulnerable communities and female farmers who may have less secure land rights (FAO 2008).

Third, natural ecosystems can be destroyed to make space for bioenergy plantations, leading to biodiversity loss. For example, the rising demand for biofuels has contributed to extensive deforestation in parts of Southeast Asia; palm oil plantations support significantly fewer species than the forest they replaced (Fitzherbert et al. 2008). Biodiversity loss may also occur through indirect land use change (see section 3.3.2). In some cases, bioenergy expansion can lead to increased biodiversity, e.g., through the establishment of perennial herbaceous plants or short-rotation woody crops in agricultural landscapes (Semere and Slater 2007).

Fourth, the impact on water resources varies greatly across feedstocks, cultivation systems and conversion technologies. While biofuels derived from irrigated crops are water intensive, use of agricultural or forestry residues or rain-fed feedstock production does not require water extraction from lakes, rivers or aquifers. But the latter might reduce downstream water availability by redirecting precipitation to crop evapotranspiration. Aquatic ecosystems might negatively be affected by leaching as well as by emissions of nutrients and pesticides. In contrast, ligno-cellulosic feedstock might decrease water demand. Water impacts can be reduced through integration in agricultural landscapes as vegetation filters to capture nutrients in passing water (Börjesson and Berndes 2006).

Fifth, the soil impacts of feedstock production (e.g., soil carbon oxidation, changed rates of soil erosion, and nutrient leaching) depend heavily on agronomic techniques and the feedstock under consideration. Similarly, the risk of soil degradation associated with using residues from agriculture or forestry heavily depends on management, yield, soil type and location. While wheat, rapeseed and corn require significant tillage (FAO 2008), crops that provide continuous cover might have a positive effect on soil outside the growing season of annual crops by reducing erosion (Berndes 2008).

The SRREN concludes that "few universal conclusions … can currently be drawn, given the multitude of rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, the multiple energy products, and the variability in environmental conditions" (Chum et al. 2011, p. 258).

3.3.5 Governance

Global, regional, national and local policies shape agricultural practices and affect bioenergy resource potential, GHG performance of bioenergy deployment and other socioeconomic and environmental dimensions. Depending on the combination of specific policy priorities, such as climate change mitigation, trade, energy security, food security or rural development, the overall policy impact can be decisive or negligible, conflicting or complementary, sustainable or unsustainable. The policy chapter of SRREN concludes that biofuel mandates and blending requirements are key drivers in the development of most modern biofuel industries (Mitchell et al. 2011). The example of Brazil is given where a combination of tax incentives, blending mandates, regulation and infrastructure investments, starting in the 1970s, produced a high share of biofuels in the overall fuel mix. More recent biofuel mandates in the U.S. and the EU, and high subsidies for corn ethanol, induced a surge in biofuel demand and deployment but were non-discriminative with respect to life-cycle GHG emissions, resulting in mostly low-cost biofuel deployment with relatively high GHG emissions. In response, the updated low-carbon fuel standard (California), renewable fuel standard (U.S.) and fuel quality directive (EU) introduce rules that discriminate based on GHG emissions (Creutzig et al. 2011). Similarly, sustainability criteria and certification schemes for bioenergy sources aim to limit harmful impacts of bioenergy deployment. The policy review in Chapter 11 is organized by end-use sectors (electricity, heating, and transport). All sectors are increasingly reliant on bioenergy. As a result, the discussion of policies relevant to bioenergy deployment is fragmented over Chapter 11.

3.4 Evaluating the bioenergy assessment

In this section, we evaluate the bioenergy assessment of the SRREN, notably its Chapters 2 ("Bioenergy") and 10 ("Mitigation Potential and Costs"). In particular, we verify whether the bioenergy assessment conforms to the assessment criteria developed in section 3.2:

- Is the assessment comprehensive in topics and communities?
- Are diverging assumptions made transparent? Is reconciliation attempted?
- Is there a consistent set of policy-relevant storylines?

Box 3.1. The role and purpose of Integrated Assessment Models

Integrated Assessment Models (IAMs) are key to the SRREN and previous Assessment Reports of the IPCC. IAMs are tools for exploring long-term and global transition pathways under various opportunities and constraints. IAM teams develop their models into different directions and aim to improve the level of detail (e.g., energy conversion technologies, etc.) and to integrate more systems (e.g., the land-use system). In addition to research of individual teams, the international community undertakes model comparison exercises. These consist of undertaking model runs with common assumptions of the policy targets and other constraints, possibly also harmonizing the assumptions on population, GDP, and other drivers. The community compares the scenario results of different transition pathways. The modelers" attention shifted to strong emission reduction in recent years, resulting in increased deployment of bioenergy in models. To systematically understand unintended side effects of land-use change, some IAMs are coupled to global land-use models.

3.4.1 Comprehensiveness

Chapter 2 of SRREN collects insights on bioenergy deployment from various disciplines and communities. Agro-economic and biophysical models of land use and availability provide the backbone for potential deployment estimates. These models also consider water availability and food security as constrains to different degrees. Studies from the life-cycle community are cited to estimate the GHG emissions of bioenergy. Techno-economic studies deliver cost estimates of various bioenergy feedstocks and pathways. Analysis of policy instruments contributes to evaluating the governance of bioenergy. The results of these contributions are summarized in section 3.3.

Social scientists, analyzing inter alia discourses, political economy, and local communities, also contribute to the huge literature on bioenergy in ways that go beyond what is captured in the SRREN. For example, human geographers and anthropologists often observe local communities and the de facto implementation of bioenergy policies and programs. A common observation is that the intended outcomes of bioenergy initiatives diverge from their real impacts (Borras et al. 2010). For example, research in India finds that despite a "pro-poor" discourse about the oilseed shrub Jatropha curcas, efforts to promote the crop have favoured resource-rich farmers and likely contributed to a widening of the wealth gap (Ariza-Montobbio et al. 2010).

Similarly, in Brazil the spread of sugar cane for bioenergy has been linked to increased social exclusion (Hall et al. 2009). Further case studies that examine the interactions between bioenergy deployment and subsistence farming reveal circumstances that have produced better or worse outcomes for local people (McCarthy 2010). Biofuel policies have also been identified as a major driver of the recent increase in both the number and size of largescale land acquisitions (Franco et al. 2010; Vermeulen and Cotula 2010), a trend with significant implications for social relations and smallholder farmers (Toulmin et al. 2011). The SRREN makes scarce reference to these studies. The use of marginal land for subsistence farming is noted as a constraint in 2.2.2.1 and 2.2.4.3, pointing out that subsistence farming may considerably, or even totally, limit the potential of marginal land for bioenergy deployment. But the social science literature on local politics is not cited or used to identify successful programs.

Another gap is that governance of bioenergy deployment is discussed in a fragmented way (see section 3.3.5). A comprehensive review of bioenergy policies, their impact on GHG emissions, deforestation, biodiversity, water and food competition is missing. As noted in 3.2, uncertainties of life-cycle emissions can be very high, constraining the reliability of policies that rely on quantitative estimates. This fundamental problem of policy making is not discussed in the SRREN.

3.4.2 Reconciliation and clarification of assumptions

The key dimensions of assessment of the future role of bioenergy are, as identified above, costs, GHG emissions, resource potential and deployment, socio-economic and environmental impacts and governance. The SRREN makes clear that projections in any of these dimensions are highly uncertain and contingent. SRREN Chapter 2 brings together research results from different types of analysis—some of which are difficult to reconcile. Based on this review of partially disparate views and the underlying methods and assumptions, several key trade-offs arise with respect to the future role of bioenergy. In SRREN Chapter 10, the IAMs explore more than 150 scenarios, some of which vary bioenergy deployment constraints exogenously. Table 3.1 specifies these different trade-offs and summarizes how the different chapters treat them.

A major gap of the SRREN bioenergy assessment was identified as the missing reconciliation between the LCA and the IAM community, representing disparate perspectives on bioenergy-associated GHG emissions (Creutzig et al. 2012). IAMs assume first-best worlds where so-called market failures, such as land-use emissions from bioenergy deployment, are addressed by appropriate policy instruments. A key result of IAMs is that low-carbon bioenergy can substitute fossil fuels, emerging as the key renewable energy source in 2050 and beyond (Fischedick et al. 2011). LCA researchers observe life-cycle emissions of biofuels that can be comparable to gasoline and are highly uncertain (Plevin et al. 2010). High deployment levels 2009; Popp et al. 2011a). and agricultural intensification (e.g., Wise et al. 2009; Popp et al. 2011b). Creutzig et al. (2012) conclude that plausible scenarios of future bioenergy deployment correlated with high bioenergy-induced GHG emissions are systematically underrepresented in the literature and in SRREN, specifically.

Table 3.1 Bioenergy trade-off characterization in SRREN.

Possible trade-offs	Insights from bioenergy experts (Chapter 2, SRREN)	Insights from integrated models (Chapter 10, SRREN)
Deployment and affordability	Higher deployment implies higher marginal land and production costs (Fig. 2.5); but higher deployment also implies economies of scale and technological learning, decreasing unit prices (Fig. 2.21)	Global bioenergy cost-supply curves are given for different land use scenarios based on SRES assumptions (Fig. 10.23). Marginal costs of biomass production increase with increasing deployment level (Fig. 10.23) but over time they decline due to land productivity improvements, learning of conversion technologies, and capital-labour substitution (10.4.4, Table 10.10). Despite being considered in some IAMs, neither assumptions nor insights from IAMs on costs are reported.
Deployment and water availability	Possible competition between bioenergy deployment and water security. Impact on water resources varies greatly across feedstocks, cultivation systems (e.g., irrigated or rain-fed) and conversion technologies (2.2.4.2, 2.5.5.1).	Briefly mentioned in 10.6.2.3: “RE can have impacts on waters, land use, soil, ecosystems and biodiversity.” Neither assumptions nor insights from IAMs on water availability are reported, mainly due to a lack of literature (van Vuuren et al. 2009).
Deployment and food security	Cited studies generally agree on a discernible contribution to food price increases by bioenergy deployment expansion, but not on the size of this contribution. This implies an overall adverse effect on food security in developing countries—particularly for high oil price development (2.5.7.4).	Only one study (de Vries et al. 2007) addresses this trade-off (10.4.4). For a food-first policy, it finds declining technical potential as a “direct consequence of more people, [. . .] hence more land demand for food production”. The assumptions made for the bioenergy supply curves (Fig. 10.23: production on abandoned and rest lands only) also imply an underlying food-first policy. No explicit information about food-security assumptions in IAMs is given. The “relationship between bioenergy production, crop production and deforestation” is identified as a knowledge gap in 10.2.4.
Deployment and climate mitigation	GHG performance of bioenergy is estimated by LCA analyses showing substantial but hugely varying life-cycle emissions for different types of bioenergy. In some cases, land-use emissions are potentially higher than the direct emissions of conventional fuels (2.5.2, 2.5.3).	For stricter mitigation targets, more bioenergy is deployed. Neither the assumptions in nor the insights from IAMs concerning co-emissions are reported. 10.2.2.4 says: “Some studies have indicated that it is the combination of bioenergy with CCS that makes low stabilization goals substantially easier through negative emissions”
Deployment and soil quality	Soil impacts of bioenergy feedstock production (e.g., soil carbon oxidation, changed rates of soil erosion, nutrient leaching) depend on agronomic techniques and feedstock. Under certain conditions, bioenergy crops can enhance carbon sequestration in soils. Residue removal could negatively impact soil carbon and fertility (2.2.4.1, 2.5.5.3).	Briefly mentioned in 10.6.2.3: “RE can have impacts on waters, land use, soil, ecosystems and biodiversity.” Neither assumptions nor insights from IAMs on water availability are reported, mainly due to a lack of literature (van Vuuren et al. 2009).
Deployment and subsistence farming	Using degraded lands for bioenergy purposes might compromise the needs of local populations for subsistence farming (2.2, 2.5.7.5).	Not mentioned.
Deployment and biodiversity	The impact of bio-crop production on biodiversity depends on crop choice, agricultural management and previous land use. Biodiversity loss may also occur indirectly. Under certain conditions, however, the effect might be positive (2.2.4.4, 2.5.5.2).	Briefly mentioned in 10.6.2.3: “RE can have impacts on waters, land use, soil, ecosystems and biodiversity”; and in 10.3.1.4: “As the available land for bioenergy is limited and competition with nature conservation issues as well as food and materials production is crucial, the sectoral use for the available bioenergy significantly depends on scenario assumptions and underlying priorities”.

Another relevant gap is the absence of trade-off specification between deployment and subsistence farming and informal markets. This seems to be related to the absence of experts on this topic. Most studies on subsistence farming emphasize the local variability of effects. The question then is under which conditions what kinds of bioenergy deployment can benefit subsistence farmers. This kind of question needs to be given greater attention, and possibly be comprehensively answered, in future bioenergy assessments.

While SRREN identifies disparate views on the future role of bioenergy and provides detailed analyses from different communities, the reconciliation of insights sometimes remains incomplete. A systematic summary, similar to Table 3.1, linking the treatment of trade-offs in Chapter 2 and 10 is not provided by SRREN. In some of the cases this is due to a lack of literature. But, more crucially, interdisciplinary communication across SRREN chapters and their respective communities is missing (for early efforts of tentative integration see (e.g., van Vuuren et al. 2009; Wise et al. 2009)). The SRREN provides little indication of how research could help to assess the salience of the respective trade-offs, e.g., through improved consequential LCA and through integrated assessment of climate, energy, economy and land use.

3.4.3 Consistent storylines

In this subsection, we evaluate storylines of Chapter 2 and Chapter 10 of SRREN, and their interaction.

3.4.3.1 Special Representative Emission Scenarios

Chum et al. develop four storylines aiming to clarify possible futures in a high-dimensional output space. For this they map their expert judgment on future bioenergy deployment on the four Special Representative Emission Scenarios (SRES), developed by the IPCC in 2000, relying on Hoogwijk et al. (2005). These scenarios represent storylines on globalization/regionalization and more environmentally sensitive versus more materially oriented world (IPCC 2000) and form the common scenario basis for the assessment of climate change and its mitigation for the climate modeling and integrated assessment communities in preparation of the Third and Fourth Assessment Reports. Each SRES bundles a set of assumptions, representing a storyline. The SRES emphasize fossil fuel availability but hardly discuss bioenergy.

In Figure 3.3, the four storylines are adapted for bioenergy following Hoogwijk et al. (2005) and organized in a matrix, regional versus global orientation, and material/economic versus environmental/social orientation. The material/economic direction is identified with poor governance, the environmental/social dimension with good governance. In the global orientation, bioenergy deployment approaches a high number of 300EJ in 2050; in the regional orientation, deployment is limited to 100EJ in 2050. The figure is built on the hypothesis that “biomass and its multiple energy products can be developed alongside food, fodder, fibre, and forest products in both sustainable and unsustainable ways”. Each storyline is associated with key preconditions and key impacts. In these storylines, Chum et al. attempt to reconcile global drivers of energy demand with the detailed analysis of a particular renewable energy source in a narrative way. This attempt is very challenging but is nonetheless a crucial exercise.

Particularly, parts of their storylines could be criticized (e.g., asking: 1) Could high deployment and poor governance imply net additional GHG emissions? 2) How do these storylines relate to the original SRES?). But the main point is to take these narrative storylines and systematically scrutinize and analyze them, taking all relevant insights on market dynamics, LCOE, resource potential, GHG emissions, water scarcity, food security, policy options and the associated trade-offs discussed in Section 3.4.2 into account, and then verify the plausibility of storylines or adapt them to consistent results of these analysis efforts in a more structured and possibly quantitative way. IAMs are understood to be the right tool to systematically analyze trade-offs and different storylines. The next section will thus present how storylines are used in the SRREN analysis of bioenergy deployment levels as derived from IAMs.

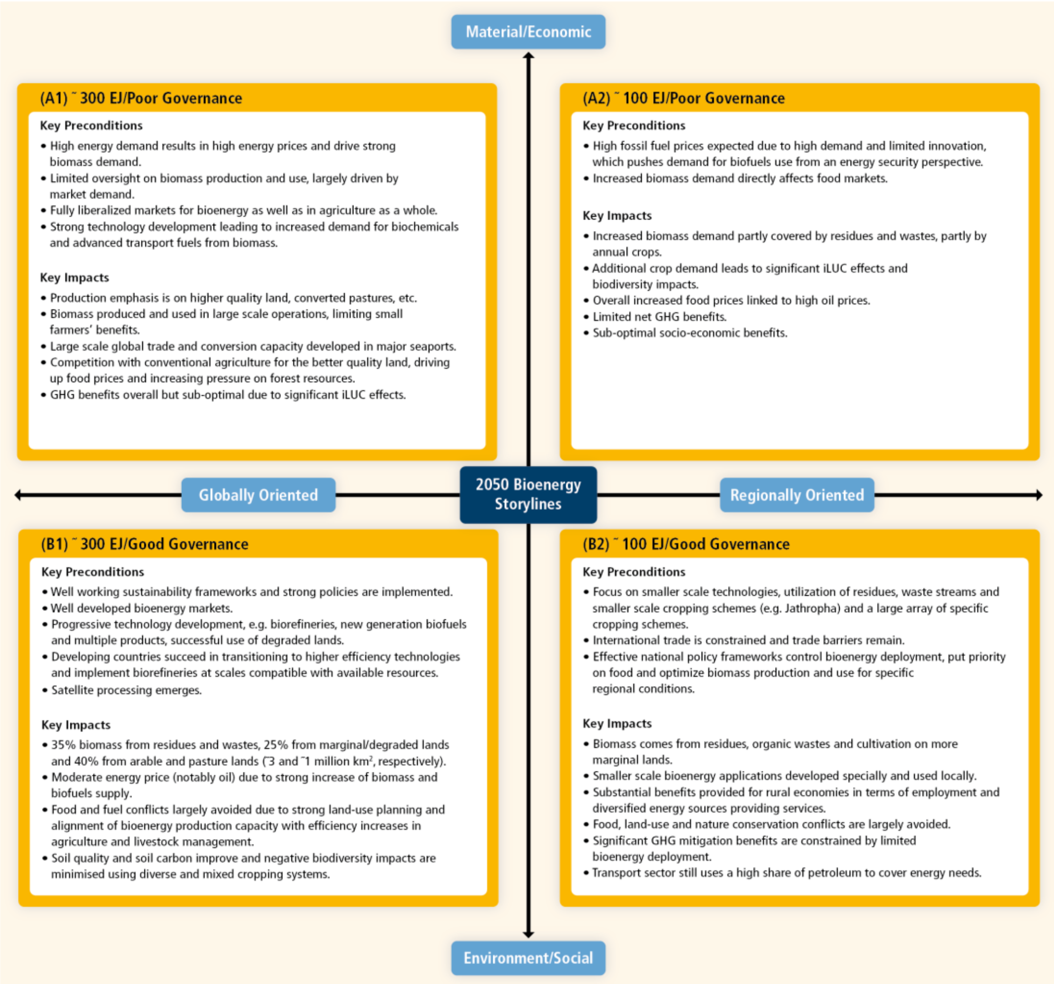

Figure 3.3 Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines (see IPCC 2000; Hoogwijk et al. 2005), taken from Chum et al. (2011, Fig. 2.27).

3.4.3.2 Modeling storylines

For energy and climate change, IAMs provide a suitable infrastructure for scenario development. Each scenario, common bundles of assumptions, represents a storyline, reflecting numerous assumptions on input parameters and model design. Specific realization and numeric representations constitute pathways. To some extent, one could call Chapter 10 of SRREN the storyline chapter. Two questions arise then: First, does the set of storylines on bioenergy cover the identified dimensions and trade-offs of SRREN Chapter 2? Second, do these storylines map on the SRES storylines, as identified above?

The IAM scenario results assessed in the SRREN cover a wide range of assumptions on economic and energy demand growth, the cost and availability of renewable energies, and competing low-carbon technologies. Only scant information is given on future bioenergy deployment. Most scenarios assume a reduction in traditional biomass, and substantial growth in modern bioenergy sources (SRREN Section 10.2.2.2), not further discriminating between different types of bioenergy. Most models do not cover the land use sector explicitly but rely on an exogenous supply cost function for bioenergy. In fact, in many models future yield improvements, land competition or land exclusion due to food production, forest protection, biodiversity, soil quality, and water scarcity are lumped into this supply cost curve. Global bioenergy cost-supply curves are given for 2050 and four different land use scenarios (SRREN Fig. 10.23) based on the same SRES storylines presented in Chapter 2 (Figure 3.3). In contrast to the potential deployment sketches in Chapter 2 also considering “poor governance” cases (A1 and A2) Chapter 10 supply cost curves assume “good governance” for all SRES storylines (A1, A2, B1, B2). This is indicated by the assumption that bioenergy is produced on abandoned and rest land only, which implies underlying food-first or nature protection policies. The maximal potentials given with the supply-curves range from 170 EJ/a (B2) to 420 EJ/a (A1) and are sufficient to cover the deployment levels of 300 EJ/a (A1, B1) and 100 EJ/a (A2, B2) presented in Chapter 2. Section 10.3.1.4 briefly points out that “the available land for bioenergy is limited and competition with nature conservation issues as well as food production is crucial” and, as a consequence, “the use of bioenergy significantly depends on scenario assumptions and underlying priorities”. However, the SRREN gives no explicit information about land availability and biomass costs assumptions in IAMs.

Many IAMs do not account for the GHG emissions from (indirect) land-use change and increased land-use intensification; in effect, bioenergy is generally assumed to be carbon neutral. Exceptions are models like POLES, IMAGE, MiniCAM and MESSAGE incorporating more detailed land use modules. In conclusion, sustainability issues related to bioenergy supply are poorly reflected in IAMs (Sathaye et al. 2011: Section 9.4).

Hence, the space of possible bioenergy storylines explored with IAMs is very narrow. Neither is the SRES scenario space of Chapter 2 systematically covered.

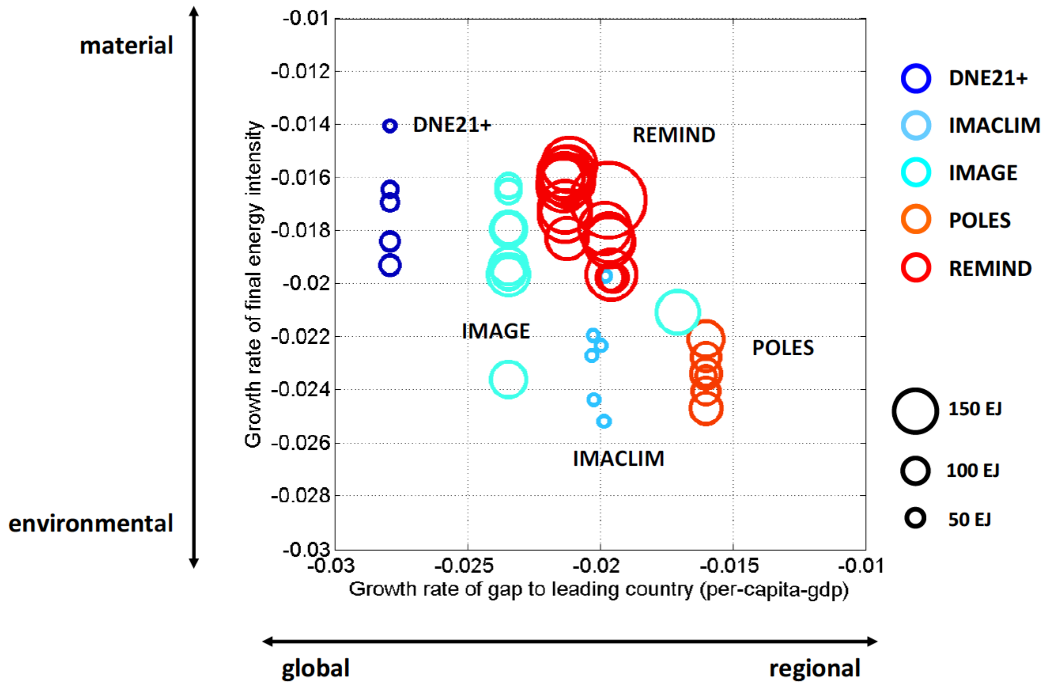

Figure 3.4 Bioenergy deployment levels (indicated by the size of the circles) of IAM scenarios along crude proxies of the SRES dimensions.

3.4.3.3 Harmonization of Storylines

Figure 3.4 visualizes the insufficient consideration of SRES dimensions in assessment models. It depicts the bioenergy deployment levels of IAMs along the same global-regional and environmental-material dimensions used for the deployment matrix in Figure 3.3. For the representation of the material-environmental dimension, we use the growth rate of global final energy intensity. Energy intensity is a shorthand for the final energy use per unit of GDP. High negative growth rates of final energy intensity indicate a rapid improvement of energy efficiency corresponding to an environmentally oriented world (Grübler 2004). To identify whether a scenario represents a globally-oriented or a regionally-oriented world, we use the convergence over time in the levels of per-capita-GDP as an indicator. More precisely we estimate the growth rate of the gap in per-capita-GDP between regions with lower income and the leading region (Barro and Sala-i-Martin 2003). High negative growth rates correspond to fast convergence and represent a “globally oriented” world. The growth rates for both axes are derived for the scenarios from 2020 to 2050 with 10-year intervals using the geometrical mean. Regional values of convergence are weighted with population to obtain a global value. The chosen indicators are the only ones related to these SRES dimensions on which a substantial number of IAMs have reported data. Other indicators would be a better fit to represent SRES dimensions (Hoogwijk et al. 2005).

The graph shows some variety of convergence across models but little or no variety of convergence in scenarios within one model. In contrast to high projections of deployment levels for a globally oriented world in Chapter 2, IAM results in Figure 3.4 show no clear sensitivity of deployment levels to any of the two depicted dimensions, not even within the models. Even acknowledging the limited possibilities to represent all relevant dimensions in highly demanding models, Figure 3.4 illustrates that IAMs insufficiently operationalize important dimensions of bioenergy supply. Harmonization of assumptions with Chapter 2 is not attempted.

Numerous specifications need to be introduced into IAMs such that a more complete scenario space, representing the trade-offs identified in SRREN Chapter 2, can be systematically explored in an integrated setting. The complexity of existing IAMs suggests that this is a highly ambitious task. Creutzig et al. (2012) suggest that more specialized models with high resolution on bioenergy but coarse-grained representation of other energy technologies can complement and soft-couple to the current model world.

3.5 Ways forward

We have summarized the state of bioenergy assessment as performed in the IPCC's Special Report on Renewable Energies. Assessments need to comprehensively present literature, reconcile disparate views by making assumptions transparent, and develop coherent storylines around varying sets of assumptions to be policy relevant. The SRREN succeeds in bringing various insights from different communities together—but insufficiently represents results from social sciences. The governance of bioenergy is discussed in a fragmented way. Trade-offs between bioenergy deployment and other essential land-use related dimensions of the biosociosphere are identified and discussed. The key trade-off between emission savings from bioenergy and emission production by induced land-use changed is not represented in the IAMs of the SRREN. Storylines of representative scenarios representing various worldviews are identified but—with the exception of deployment costs—not systematically explored in models. The report remains largely silent on possible trade-offs and risks related to variations on induced co-emissions and impacts on human living condition on a global scale, but also in regional or local settings. This chapter has considered how the SRREN performed in relation to the discussed assessment requirements. Understanding why it did so, and how its gaps could realistically be filled, would require considering a broader set of issues including the institutional context. The integrated assessment community is currently working on a new class of storylines, the so-called shared socio-economic pathways (see Kriegler et al. 2010; Arnell et al. 2011). We express the hope that this process, together with upcoming assessments, fills the gaps left by the SRREN and leads to further improved exploration of bioenergy futures.

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3.7 References

Agrawala, S. 1998. "Structural and Process History of the Intergovernmental Panel on Climate Change." *Climatic Change* 39(4): 621–642. http://dx.doi.org/10.1023/A:1005312331477.

Ariza-Montobbio, P., L. Sharachchandra, K. Giorgos, and J. Martinez-Alier. 2010. "The Political Ecology of Jatropha Plantations for Biodiesel in Tamil Nadu, India." *Journal of Peasant Studies* 37(4): 875–897. http://dx.doi.org/10.1080/03066150.2010.512462.

Arnell, N., T. Kram, T. Carter, K. Ebi, J. Edmonds, S. Hallegatte, E. Kriegler, et al. 2011. "A framework for a New Generation of Socioeconomic Scenarios for Climate Change Impact, Adaptation, Vulnerability, and Mitigation Research. http://www.isp.ucar.edu/socio-economic-pathways.

Barro, R.J. and X. Sala-i-Martin. 2003. *Economic Growth*, Cambridge, MA, USA: The MIT Press.

Beck, S. 2010. "Moving Beyond the Linear Model of Expertise? IPCC and the Test of Adaptation." *Regional Environmental Change* 11(2): 297–306. http://dx.doi.org/10.1007/s10113-010-0136-2.

Berndes, G. 2008. "Future Biomass Energy Supply: The Consumptive Water Use Perspective." *International Journal of Water Resources Development* 24(2): 235–245. http://dx.doi.org/10.1080/07900620701723489.

Borras, S. M., P. McMichael and I. Scoones. 2010. "The Politics of Biofuels, Land and Agrarian Change: Editors' Introduction." *Journal of Peasant Studies* 37(4): 575–592. http://dx.doi.org/10.1080/03066150.2010.512448 .

Börjesson, P. and G. Berndes. 2006. "The Prospects for Willow Plantations for Wastewater Treatment in Sweden." *Biomass and Bioenergy* 30(5) (May): 428–438. http://dx.doi.org/10.1016/j.biombioe.2005.11.018.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, and J. Jäger. 2002. "Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making." *SSRN eLibrary* (November). http://papers.ssrn.com/sol3/papers.cfm?abstract_id=372280.

Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, et al. 2011. "Bioenergy." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. Von Stechow (eds)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139151153.006.

Creutzig, F. and D.M. Kammen. 2009. "Getting the Carbon Out of Transportation Fuels." In *H. J. Schellnhuber, M. Molina, N. Stern, V. Huber & S. Kadner (Eds.), Global Sustainability—A Nobel Cause*. Cambridge, UK: Cambridge University Press.

Creutzig, F., E. McGlynn, J. Minx, and O. Edenhofer. 2011. "Climate Policies for Road Transport Revisited (I): Evaluation of the Current Framework." *Energy Policy* 39(5): 2396–2406. http://dx.doi.org/10.1016/j.enpol.2011.01.062.

Creutzig, F., A. Popp, R.J. Plevin, G. Luderer, J. Minx, and O. Edenhofer. 2012. "Reconciling Top-down and Bottom-up Modeling on Future Bioenergy Deployment." *Nature Climate Change* 2: 320–327.

Crutzen, P.J., A.R. Mosier, K.A. Smith, and W. Winiwarter. 2008. "N2O Release from Agro-biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels." *Atmospheric Chemistry and Physics* 8: 389–395. http://dx.doi.org/10.5194/acp-8-389-2008.

Dewey, J. 1988. "Theory of Valuation." In *John Dewey. The Later Works, 1925–1953, Volume 13: 1938–1939*, ed. J.A. Boydston, 189–251. Carbondale and Edwardsville: Southern Illinois Press.

Dornburg, V., D. van Vuuren, G. van de Ven, et al. 2010. "Bioenergy Revisited: Key Factors in Global Potentials of Bioenergy." *Energy and Environmental Science* 3: 258–267. http://dx.doi.org/10.1039/b922422j.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, et al. 2010. "The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs." *The Energy Journal* 31 (Special Issue 1): 11–48.

Edenhofer, O. and K. Seyboth. 2013. "Intergovernmental Panel on Climate Change." In *Encyclopedia of Energy, Natural Resource and Environmental Economics*, ed. J.F. Shogren. San Diego: Elsevier. https://doi.org/10.1016/B978-0-12-375067-9.00128-5.

FAO. 2008. *The State of Food and Agriculture 2008—Biofuels: Prospects, Risks, and Opportunities*. Rome, Italy: Food and Agriculture Organization.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science* 319: 1235–1238. http://dx.doi.org/10.1126/science.1152747.

Fargione, J., R.J. Plevin, and J. Hill. 2010. "The Ecological Impact of Biofuels." *Annual Review of Ecology, Evolution and Systematics* 41: 351–377. http://dx.doi.org/10.1146/annurev-ecolsys-102209-144720.

Farrell, A.E., and J. Jäger, eds. 2006. *Assessments of Regional and Global Environmental Risks. Designing Processes for the Effective Use of Science in Decisionmaking*. Washington, DC, USA: Resources for the Future.

Fischedick, M., R. Schaeffer, A. Adedoyin, M. Akai, T. Bruckner, L. Clarke, V. Krey, et al. 2011. "Mitigation Potential and Costs." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. Von Stechow (eds)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139151153.014.

Fitzherbert, E. B., M. J. Struebig, A. Morel, F. Danielsen, C. A. Brühl, P. F. Donald, and B. Phalan. 2008. "How Will Oil Palm Expansion Affect Biodiversity?" *Trends in Ecology & Evolution* 23(10) (October): 538–545. http://dx.doi.org/10.1016/j.tree.2008.06.012.

Franco, J., Les Levidow, D. Fig, L. Goldfarb, M. Hönicke, and M. L. Mendonça. 2010. "Assumptions in the European Union Biofuels Policy: Frictions with Experiences in Germany, Brazil and Mozambique." *Journal of Peasant Studies* 37(4): 661–698. https://doi.org/10.1080/03066150.2010.512454.

Grübler, A. 2004. "Transitions in Energy Use." *Encyclopedia of Energy* 6: 163–177.

Haas, P.M. 1992. "Epistemic Communities and International-Policy Coordination–Introduction." *International Organization* 46(1): 1–35. http://dx.doi.org/10.1017/S0020818300001442.

Haberl, H., T. Beringer, S.C. Bhattacharya, K.-H. Erb, and M. Hoogwijk. 2010. "The Global Technical Potential of Bio-energy in 2050 Considering Sustainability Constraints." *Current Opinion in Environmental Sustainability* 2: 394–403. http://dx.doi.org/10.1016/j.cosust.2010.10.007.

Hall, J., S. Matos, L. Severino, and N. Beltraõ. 2009. "Brazilian Biofuels and Social Exclusion: Established and Concentrated Ethanol Versus Emerging and Dispersed Biodiesel." *Journal of Cleaner Production* 17, Supplement 1 (November): S77–S85. http://dx.doi.org/10.1016/j.jclepro.2009.01.003.

Hertel, T.W., A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen. 2009. *Global Land Use and Greenhouse Gas Emissions Impacts of U.S. Maize Ethanol: Estimating Market-Mediated Responses*. GTAP Working Paper No. 55. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. file://localhost/Users/rjp/literature/h/Hertel%20-%20Effects%20of%20US%20maize%20ethanol%202010.pdf.

Hoogwijk, M., P.C.A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg. 2005. "Potential of Biomass Energy Out to 2100, for Four IPCC SRES Land-use Scenarios." *Biomass and Bioenergy* 29(4): 225–257. http://dx.doi.org/10.1016/j.biombioe.2005.05.002.

IPCC. 2000*. Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Ed. N. Nakicenovic and R. Swart. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

———. 2007. *Climate Change 2007: Synthesis Report. Contributions of Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri, and A. Reisinger (eds)*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

———. 2011a. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

———. 2011b. "Procedures for the Preparation for the Review, Acceptance, Adoption, Approval and Publication of IPCC Reports. Appendix A to the Principles Governing IPCC Work."

Keller, A.C. 2010. "Credibility and Relevance in Environmental Policy: Measuring Strategies and Performance Among Science Assessment Organizations." *Journal of Public Administration Research and Theory*, 20(2): 357–386. http://dx.doi.org/10.1093/jopart/mup001.

Kriegler, E., B. O'Neill, S. Hallegatte, T. Kram, R. Lempert, R. Moss, and T. Wilbanks. 2010. Socio-economic scenario development for climate change analysis. CIRED Working Papers hal-00866437 (https://ideas.repec.org/p/hal/ciredw/hal-00866437.html).

MA. 2005. *Millennium Ecosystem Assessment*. Washington, DC: Island Press.

Malca, J. and F. Freire. 2010. "Uncertainty Analysis in Biofuel Systems: An Application to the Life Cycle of Rapeseed Oil." *Journal of Industrial Ecology* 14(2): 322–334. http://dx.doi.org/10.1111/j.1530-9290.2010.00227.x.

Mastrandrea, M., K. Mach, G.-K. Plattner, O. Edenhofer, T. Stocker, C. Field, K. Ebi, and P. Matschoss. 2011. "The IPCC AR5 Guidance Note on Consistent Treatment of Uncertainties: a Common Approach Across the Working Groups." *Climatic Change* 108(4): 675–691. http://dx.doi.org/10.1007/s10584-011-0178-6.

McCarthy, J.F. 2010. "Processes of Inclusion and Adverse Incorporation: Oil Palm and Agrarian Change in Sumatra, Indonesia." *Journal of Peasant Studies* 37(4): 821–850. http://dx.doi.org/10.1080/03066150.2010.512460.

Melillo, J.M., John M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser. 2009. "Indirect Emissions from Biofuels: How Important?" *Science* 326(5958):1397–1399. http://dx.doi.org/10.1126/science.1180251.

Mitchell, C., J.L. Sawin, G.R. Pokharel, D. Kammen, Z. Wang, S. Fifita, M. Jaccard, et al. 2011. "Policy, Financing and Implementation." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139151153.015

Mitchell, Ronald Bruce, William C. Clark, D.W. Cash, and Nancy M. Dickson. 2006. *Global Environmental Assessments: Information and Influence*. Cambridge, MA, USA: MIT Press.

Pielke, R.A., Jr. 2007. *The Honest Broker*. Cambridge: Cambridge University Press.

Plevin, R.J. M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs. 2010. "Greenhouse Gas Emissions from Biofuels: Indirect Land Use Change Are Uncertain but May Be Much Greater Than Previously Estimated." *Environmental Science & Technology* 44(21): 8015–8021. http://dx.doi.org/10.1021/es101946t.

Popp, A., J. Dietrich, H. Lotze-Campen, D. Klein, N. Bauer, M. Krause, T. Beringer, D. Gerten, and O. Edenhofer. "The Potential Contribution of Bioenergy to Climate Change Mitigation Including Its Costs and Side Effects." *Environmental Research Letters* 6(3): 034017. http://dx.doi.org/10.1088/1748-9326/6/3/034017.

Popp, A., H. Lotze-Campen, M. Leimbach, B. Knopf, T. Beringer, N. Bauer, and B. Bodirsky. "On Sustainability of Bioenergy Production: Integrating Co-emissions from Agricultural Intensification." *Biomass and Bioenergy* 35(12): 4770–4780. http://dx.doi.org/10.1016/j.biombioe.2010.06.014.

Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrota. 2011. *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Cambridge, UK: Cambridge University Press.

Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, et al. 2011. "Renewable Energy in the Context of Sustainable Development." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139151153.013.

Semere, T., and F.M. Slater. 2007. "Ground Flora, Small Mammal and Bird Species Diversity in Miscanthus (Miscanthus-giganteus) and Reed Canary-grass (Phalaris Arundinacea) Fields." *Biomass and Bioenergy* 31(1) (January): 20–29. http://dx.doi.org/10.1016/j.biombioe.2006.07.001.

van der Sluijs, J.P., A.C. Petersen, P.H.M. Janssen, J.S. Risbey, and J.R. Ravetz. 2008. "Exploring the Quality of Evidence for Complex and Contested Policy Decisions." *Environmental Research Letters* 3(2) (April): 024008. http://dx.doi.org/10.1088/1748-9326/3/2/024008.

Smeets, E.M.W., A.P.C. Faaij, I. Lemandowski, and W. Turkenburg. 2007. "A Bottom-up Assessment and Review of Global Bio-energy Potentials to 2050." *Progress in Energy and Combustion Science* 33(1): 56–106. http://dx.doi.org/10.1016/j.pecs.2006.08.001.

Toulmin, C., S. Borras, B. Bindraban, C. Mwangi, and S. Sauer. 2011. *Land Tenure and International Investments in Agriculture: a Report by the UN Committee on Food Security High Level Panel of Experts*. Rome: Food and Agriculture Organization of the United Nations.

Vermeulen, S., and L.Cotula. 2010. "Over the Heads of Local People: Consultation, Consent, and Recompense in Large-scale Land Deals for Biofuels Projects in Africa." *Journal of Peasant Studies* 37(4): 899–916. http://dx.doi.org/10.1080/03066150.2010.512463.
de Vries, B.J.M., D.P. van Vuuren, and M. Hoogwijk. 2007. "Renewable Energy Sources: Their Global Potential for the First-half of the 21st Century at a Global Level: An Integrated Approach. *Energy Policy* 35(4) (April): 2590–2610. http://dx.doi.org/10.1016/j.enpol.2006.09.002.
van Vuuren, D., J. van Vliet, and E. Stehfest. 2009. "Future Bio-energy Potential Under Various Natural Constraints." *Energy Policy* 37: 4220–4230. http://dx.doi.org/10.1016/j.enpol.2009.05.029.
Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds. 2009. "Implications of Limiting CO_2 Concentrations for Land Use and Energy." *Science* 324(5931): 1183–1186. http://dx.doi.org/10.1126/science.1168475.
World Bank. 2009. *The World Bank—Global Economic Prospects—Commodities at the Crossroad*. Washington D.C., USA: The World Bank, The International Bank for Reconstruction and Development.

4 Linking climate change mitigation research to sustainable development

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4.1 Introduction

Sustainable development (SD) is a normative concept of intergenerational justice according to which the capability of future generations to attain their well-being should be sustained (WCED, 1987). As a consequence, concerns about the adaptation to and the mitigation of climate change are deeply embedded in the conceptual framework of SD and were politically and formally linked at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil in 1992, concluding that greenhouse gases (GHG) should be stabilized at a level that would avoid dangerous climate change.

So far, attempts to decouple economic growth from rising GHG emissions at a global scale have proven unsuccessful, with world-wide emissions continuing to rise at rapid pace (Peters et al., 2013). It becomes increasingly clear that, over the long term, the limiting factor of global energy supply is not the scarcity of fossil fuels but is rather the limited disposal space of the atmosphere implied by climate stabilization targets. It is meanwhile well established that there is a direct link between cumulative carbon dioxide (CO_2) emissions and long-term global warming. As a consequence, only a limited emissions budget remains available if temperature change is to be kept below a certain threshold level (Stocker et al., 2013). The UNFCCC formulates the normative objective of "avoiding dangerous anthropogenic interference with the climate system" (UNFCCC, 1992), which was later translated into the long-term goal of limiting global warming to 2°C relative to pre-industrial levels (UNFCCC, 2010). This target can be understood as a possible operationalization of SD in the context of mitigation.

The mitigation of climate change requires a transformation pathway that entails large reductions in GHG emissions (see Edenhofer and Flachsland, 2012; Edenhofer et al., 2013a; Kriegler et al., 2013a). Figure 4.1 provides a conceptual overview of the range of mitigation policies and measures available for such transformation pathways. In the context of mitigation studies population policies and policies addressing consumption-related lifestyle changes are very often omitted because it requires an in-depth analysis of the related ethical, social and economic problems. We will discuss these as a challenge for future research in the area of mitigation and SD (see section 4.4.2).

When aiming to determine the optimal level of climate change mitigation or to compose a portfolio of mitigation options for alternative climate stabilization targets, no clear guidance regarding the use of adequate evaluation criteria exists. Here, the concept of weak and strong sustainability can provide a reasonable entry point. In general, SD evaluates long-term socio-economic pathways according to a multi-objective social welfare function which aggregates different societal goals from a public policy perspective. The paradigms of the two approaches differ in the underlying assumption about the substitutability of different societal goals. Weak sustainability is based on the idea that only the aggregate stock of capital, including social, natural and physical capital, needs to be sustained for the well-being of future generations. This implies that environmental degradation or use of the atmosphere as a disposal space for CO_2 can be compensated by man-made capital. As such, weak sustainability can be seen as consistent with an intertemporal cost-benefit analysis (CBA) which calculates the optimal composition of the total capital stock according to the applied social welfare function. However, the optimal pathway is only sustainable if the consumption stream does not deteriorate the capacity of the economy to produce consumption (see Weitzman, 2003, pp. 244-94 for a formal discussion). It is worthwhile to note that a consistent CBA also requires a comprehensive understanding of the costs of adaptation to climate change. As a consequence, the optimal level of mitigation and adaptation is determined simultaneously in such analyses.

Strong sustainability can be viewed as imposing guardrails on socio-economic pathways, beyond which no opportunity to compensate environmental degradation with the accumulation of man-made capital exists. According to this approach, some stocks, such as the rainforest, are considered so precious that they should not be driven down at any price. Therefore, strong sustainability can be perceived as the non-substitutability paradigm. In the context of mitigation, GHG concentration levels are imposed as guardrails beyond which the risks of climate change may become unmanageable for socio-economic systems. These guardrails or planetary boundary conditions are often motivated by non-linearities, discontinuities or non-convexities (see Neumayer, 2003 and Sathaye et al., 2011). This concept is consistent with an intertemporal cost-effectiveness analysis (CEA) which calculates social welfare optima subject to these boundary conditions. The guardrails used in the CEA also define the division of labour between mitigation and adaptation. However, in contrast to the CBA, adaptation is not determined at its optimal level but as a required effort to deal with the remaining climate change impacts.

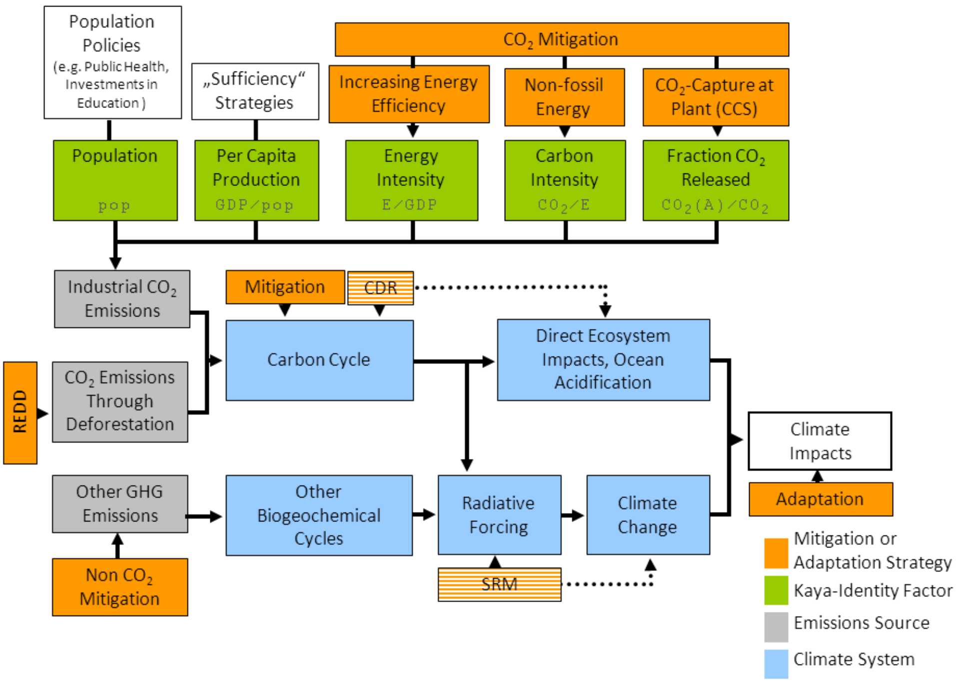

Figure 4.1 Schematic visualization of the technology and policy-based solutions space relative to the mitigation of and adaptation to climate change. CDR represents Carbon Dioxide Removal Technologies. SRM represents Solar Radiation Management technologies. REDD represents Reducing Emissions from Deforestation and Degradation. Source: Used with permission of Annual Reviews, from Edenhofer et al. (2013a) On the Sustainability of Renewable Energy Sources. *Annu. Rev. Environ. Resour.* 38: 169–200; permission conveyed in 2022 through Copyright Clearance Center, Inc.

This chapter is organized in the following way. In section 4.2 we conceptualize strong and weak sustainability in a simple multi-objective framework. From the perspective of normative welfare theory, we explore the implication of multiple objectives for the evaluation of socio-economic pathways. In section 4.3 we will discuss an important tool of applied sustainability research – integrated assessment models (IAMs). These large-scale numerical models can be broadly grouped into two categories: CBA-based IAMs for determining the optimal mitigation pathway, and CEA-based IAMs for identifying the optimal portfolio of mitigation options for a given concentration level. IAMs have become an important tool to explore climate stabilization pathways by providing insight into the role of different technological mitigation options and the related costs and risks on a global scale and over long-time horizons. By integrating insights from different disciplines, e.g., on atmospheric composition, the climate system, human activities and their global macroeconomic dynamics, and ecosystem functions, they are the only tools in the mitigation literature that can combine models of both biogeophysical and human processes and their connections and feedbacks. Section 4.4 discusses future research directions to improve the understanding of the linkage between climate change mitigation and SD, followed by concluding remarks in section 4.5.

4.2 Mitigation pathways and SD: A welfare -theoretic framework for analysis

The concept of SD is open to a multitude of opinions regarding which societal objectives should be taken into account in the discussion of current and future well-being. The question regarding the most appropriate interpretation is addressed in the research on normative welfare theory which – explicitly or implicitly – derives indicators allowing for an evaluation of socio-economic development.

In order to conceptualize strong and weak sustainability we will resort to an example, which can be generalized and extended in many ways. We assume that utility at time t depends on three factors: consumption C_t, the state of the climate W_t and health H_t. Intertemporal utility is thus:

(1)

$$\int_0^\infty e^{-\rho t} U(C_t, W_t, H_t) dt$$

where $U_C > 0, U_W < 0, U_H > 0$. Although there is an intensive debate on the right way of discounting, we use here the standard approach of a constant pure time preference rate ρ. This pure time preference rate can be best understood as a normative focal point. However, we will not discuss which pure time rate is appropriate from an ethical perspective (for this discussion see Gollier, 2012, and Hepburn and Gosnell, 2014). Production requires capital K and pollution[7] P, so that the production function is:

[7] This is a simplifying way of modeling the use of pollution-intensive fuels in production. These fuels emit CO_2 which has an effect on the climate as in equation (3) and also release other health relevant pollutants as in equation (4) (see Smith et al., 2009 and Rao et al., 2012).

(2)

$$F(K_t, P_t)$$

where $F_K > 0$ and $F_P > 0$ as always.

The state of the climate is measured as CO_2 concentration and pollution is measured in units of CO_2 concentration implied by their emission. The CO_2 concentration W therefore increases with additional pollution:[8]

(3)

$$\dot{W}_t = P_t \ .$$

The state of health depends on investments into the health system $I_{H,t}$, but also on air quality. This reflects that industrially generated pollution increases the risk of respiratory diseases and other health problems. The state of health thus evolves according to

(4)

$$\dot{H}_t = G(P_t, I_{H,t})$$

where $G_P < 0$ and $G_{I_{H,t}} > 0$. The remaining state variable is capital, for which the law of motion is

(5)

$$\dot{K}_t = I_{K,t} = F(K_t, P_t) - C_t - I_{H,t}.$$

The social planner of this economy maximizes (1) with respect to the state variable evolution in equations (3), (4) and (5). The resulting Hamiltonian is

(6)

$$H = \mathrm{U(C, W, H)} + \lambda_\mathrm{K}(\mathrm{F(K, P)} - \mathrm{C} - \mathrm{I_H}) + \lambda_\mathrm{W}\mathrm{P} + \lambda_\mathrm{H}\mathrm{G(P, I_H)},$$

where λ_i is the shadow value of stock i. The first order conditions include

(7)

$$\mathrm{U_C} - \lambda_\mathrm{K} = 0,$$

(8)

$$-\lambda_K + \lambda_H G_{I_H} = 0,$$

(9)

$$\lambda_W + \lambda_K F_P + \lambda_H G_P = 0.$$

---

[8] Note should be taken that equation (3) is a deliberate and broad simplification for illustrative purposes and not intended to provide a detailed representation of the carbon cycle.

Substituting the shadow prices into the Hamiltonian we obtain

(10)

$$H = U(C,W,H) + U_C I_K + \left(- U_C F_P - \frac{U_C}{G_{I_H}} G_P \right) P \ + \ \frac{U_C}{G_{I_H}} G(P, I_H).$$

To continue with the example, we follow the approach by Perman et al. (1996, Appendix 19.2), and assume that utility is linear in all its arguments

(11)

$$U(C,W,H) = U_C C + U_W W \ + U_H H.$$

We make this assumption in order to simplify the calculation. It can also be seen as a first order approximation, an approach justified in Weitzman (2000).

Next, we substitute (11) into (10) and divide by U_C in order to obtain the Hamiltonian in monetary terms

(12)

$$\frac{H}{U_C} = C + \frac{U_W}{U_C} W + \frac{U_H}{U_C} H + I_K + \left(-F_P - \frac{G_P}{G_{I_H}} \right) P \ + \frac{1}{G_{I_H}} \ G(P, I_H).$$

This equation represents the net national product (NNP) in our example economy and permits an understanding of the interaction between the three factors consumption, health and the state of the climate, which are discussed in the next section.

4.2.1 Shifting priorities: Weighting multiple objectives

Quite naturally, all those socio-economic variables which contribute to well-being should be considered as individual objectives. In our example economy these objectives are consumption, the state of the climate and health and the Hamiltonian shows how they should be taken into account. One part of it is GDP, which is given as the sum of consumption C and investments into capital I_K. To this, the state of the climate $\frac{U_W}{U_C} W$ should be added as well as 'investments into climate', $\left(-F_P - \frac{G_P}{G_{I_H}} \right) P$. Note that pollution enters here as a negative term as long as $P > 0$. Finally, the state of health $\frac{U_H}{U_C} H$ is added and investments into health $\frac{1}{G_{I_H}} G(P, I_H)$.

This welfare-theoretic framework not only informs about what should be included but also how it should be weighted compared to other benefits (see Box 4.1 for an application to the notion of co-benefits). The reference value will be consumption, so consumption enters the indicator with weight 1. In our simple example economy, the state of the climate and health enter the objective function weighted with their respective marginal rate of substitution (MRS) with consumption. The MRS says at which rates units of consumption can be converted into units of climate quality or health levels without changing the level of utility. Capital investments can be transformed one-to-one into consumption, thus having the same weight. The weights attached to the investments into climate and health are the rates at which they can be converted into consumption. Taking the part $-F_P P$ as an example, F_P is the marginal rate of productivity from pollution, i.e. the rate at which pollution can be converted into output (which can then be used for consumption or capital investment).

Box 4.1. Synergies and co-benefits in a multiple objectives framework

The right handling of co-benefits is a contentious issue among environmental economists (see Krupnick et al., 2000). The word seems to imply that some objectives are reached (or not reached) as a by-product of pursuing other objectives without being explicit about the interactions between the various objectives and overall social welfare.[9] This raises the concern that these additional objectives and the associated policy instruments will not be taken sufficiently seriously in their own right (cf. Dubash et al., 2013). The welfare-theoretic framework offers a different perspective that allows identifying and quantifying synergies across objectives without neglecting any particular one.

In the context of our simple example economy, one objective of reducing pollution is to stabilize CO_2 concentrations. Reducing pollution, however, also has benefits for public health, as modeled in equation (4). The main benefit of reducing emissions would then be represented by the term $-F_P P$ in equation (12) and in the improvement of the state of the climate W. The synergy between mitigation and public health would be represented by the effect on health, $-\frac{G_P}{G_{I_H}} P$ and on the state of health H. Although real-world settings are, of course, more complex, this simple welfare framework provides a useful intuition about the interactions across different objectives and overall social welfare: to assess a particular mitigation option comprehensively, the net welfare effect is decisive rather than benefits for individual objectives. Mitigation will reduce consumption, limit global warming and improve public health. It should thus be pursued if the sum of these three (the net welfare effect) is positive. If the net effect turns negative, it should not be pursued any further because the loss in consumption outweighs the positive effects for global warming and public health.

It is an unresolved issue in the current debate about which objectives should be included in a social welfare function. The so-called 'Sustainable Development Goals' (Griggs et al., 2013) that are envisaged to extend the Millennium Development Goals (MDGs) could be reasonable candidates. They include conditions necessary to assure the stability of the Earth system and proposals for adding issues such as climate change, unemployment, inequality and global market instability to the MDGs (Fukuda-Parr, 2012). It is worthwhile to note that minimum thresholds or 'guardrails' for access to crucial infrastructure services of poor people could be explored in order to identify the costs, risks and benefits of these objectives or guardrails.

[9] By the term 'co-benefit', we refer here to the non-monetary positive co-effects of pursuing one objective on additional objectives, whereas the term 'adverse side-effect' denotes the antonym (cf. Edenhofer et al., 2013a).

In the public debate on climate change, the notion of co-benefits is particularly prominent for situations when decentralized agents have insufficient incentives to act in a way that would be consistent with the welfare optimum because of inappropriate policies. In this so-called second-best setting, for example when health policies are sub-optimal, mitigation can have co-benefits on public health which then entail net welfare gains until the optimal levels of mitigation and health are reached. However, the notion of co-benefits should not divert attention from the goal of reaching the social optimum across the multitude of objectives associated with SD. Future research on SD should hence focus not only on the exploration of synergies and trade-offs between societal goals, but also on the existence of multiple externalities and the interaction between multiple policy instruments (see Edenhofer et al., 2013a and Kolstadt et al., 2014, for a more extensive discussion).

4.2.2 Flexible boundaries: Reconciling weak and strong sustainability

Among environmentalists, there is a passionate debate on whether strong or weak sustainability is the right approach to SD (see, for example, Ekins, 2014 and Randall, 2014). The proposed welfare-theoretic framework of SD reconciles these two positions on a formal level. When deciding whether or not to emit another unit of pollution, the society pursuing SD trades off the benefit of having higher consumption against the benefit of less climate change. The price for 'trading' the two in this case is the MRS, $\frac{U_W}{U_C}$, which corresponds to the weak sustainability approach. The framework is, however, able to implement 'red lines' as well. Consider for example that a certain level W^* of CO_2 concentration should not be crossed, because an irreversible catastrophe would occur. Then utility would approach minus infinity at this point, $lim_{W \to W^*} U(C, W, H) = -\infty$. Since utility is central for wealth (see equation (10)), wealth would reduce to minus infinity as well. Any welfare maximization would thus stay well clear of W^*, simply because the price of approaching it would be punishingly high.

One of the most important aspects to note though is that a certain point of an irreversible catastrophe does not exist. Instead, there is great uncertainty on the limits of sustainability (Kunreuther et al., 2013). The climate system in particular relies on many uncertain factors, which in turn interact in an uncertain way. These uncertainties imply that beyond certain thresholds of atmospheric GHG concentrations there is a substantial probability of very dramatic negative consequences, so-called 'fat tails'. Given the existence of fat tails, Weitzman (2009) arrives at a 'dismal theorem', which says that the expected value of the stochastic discount factor is infinity. Although the analysis has been questioned thoroughly (Millner, 2013), the possibility remains that the framework is valid. Pindyck (2013) concludes that the uncertainties are so high that no reliable social cost of carbon can be estimated, thus making CBA meaningless (see also section 4.3.1.1). Weitzman (2012) thus suggests the introduction of targets, which would play the role of 'red lines' near which the price soars. They would guide society away from further exploiting resources, such as using the atmosphere as an infinite disposal space for CO_2.

4.2.3 Towards improved welfare indicators

The proposed framework allows linking the SD debate to the ongoing debate on GDP as a welfare indicator and as a goal for economic and environmental policy. Fleurbaey (2009) critically examines four categories of welfare indicators. While each of the categories has some strength in measuring welfare and determining objectives, there is no consensus candidate yet and practical implementation poses a considerable challenge.

NNP, as used in our example above, falls into the category of 'corrected GDP'. While it can provide systematic, transparent and theoretically founded guidance in translating society's objectives into policies and investment decisions, see Weitzman (2003), it can be criticized from many angles. Fleurbaey (2009) points out that, among other shortcomings, NNP does not take inequality into account. However, it constitutes a formidable tool for broadening the perspective from climate change mitigation to SD in a consistent and easily accessible way, as such laying the ground for the discussion on how integrated assessment models (IAMs) can be related to SD in the next section.

Performing the exemplary calculation of NNP provided us with three key insights. The first insight is on the combination and comparison of multiple objectives. Once we have defined a complete utility function, NNP will reveal which socio-economic variables need to be measured and how they need to be weighted from a theoretical perspective. The second insight is on the relation between weak and strong sustainability. Once it is established at which point a stock (like the state of the climate, the level of biodiversity or the amount of rain forest) reaches a critical threshold, NNP will inform us on how much we need to invest to avoid reaching this threshold. The third insight is on synergies. NNP demonstrates that each stock needs to be used and preserved in its own right and no objective can be considered a 'side-effect'. Welfare indicators in general, and NNP as one example, can thus guide the development of IAMs from one or two objectives towards a multiple objectives approach to SD and the associated challenges.

4.3 Applied tools in sustainability science: Integrated assessment models

Based on the insights from the welfare-theoretic framework discussed above, this section will look at an important tool of applied sustainability research – the IAMs – to clarify the links of IAMs to the sustainability debate. Following the classification of Edenhofer et al. (2006 and 2010), this section focuses on optimal growth models and energy systems models that are able to calculate intertemporal optima – such as done in section 4.2 for our simple example economy.[10]

Results derived from recursive-dynamic models of the energy-economic system are omitted because of their inability to calculate such intertemporal optima. Also the recent development in climate economics to apply overlapping generation models for

[10] For CEA-based IAMs considered here, recent developments have made the difference between the two categories much smaller because many models incorporate important aspects of the other approach and are also referred to as 'hybrid models' (Hourecade et al., 2006; van Vuuren et al., 2009) or large-scale integrated models (Fischedick et al., 2011).

the design of climate policy is not discussed because of the premature status of these models. In this section we focus on results from CEA-based IAMs because of the inherent uncertainties of the climate damages (see section 4.2.2). This is the reason why international assessment bodies like the Intergovernmental Panel on Climate Change (IPCC), but also reports like the United Nations Environmental Programme (UNEP) Emissions Gap Report, rely on such results (IPCC, 2007; IPCC, 2014; UNEP, 2012). In their recent development, CEA-based IAMs have not only derived their results based on idealized scenarios but also for so-called 'imperfect worlds' – mainly along two dimensions: sub-optimal climate policies and limited availability of technologies (see Clarke et al., 2014 and section 4.3.2.1). For the sake of clarity, we will visualize results from one recent study based on one of the IAMs, REMIND, and embed these results in the broader context of recent modeling comparison exercises. These insights might be helpful for a better understanding of the underlying technical, economic and political requirements of low stabilization scenarios which are used by international climate negotiators (Edenhofer et al., 2014).

In addition, the following section will discuss how the weak and strong sustainability paradigms are reflected in the IAM literature (section 4.3.1) and present recent attempts to take into account multiple objectives beyond mitigation (section 4.3.2).

4.3.1 Strong and weak sustainability approaches in IAM scenario literature

While the different approaches to integrated assessment modeling implicitly subscribe to different perspectives on the weak versus strong sustainability debate, they have been designed to answer rather specific research questions instead of making explicit contributions to the theoretical SD debate.

4.3.1.1 Weak sustainability and the social cost of carbon

CBA-based IAMs analyze costs and benefits for different emission levels based on a utility function that sometimes combines consumption with other continuous variables, such as health (see section 4.3.2.1). They aim to find the optimal amount of mitigation by comparing the associated costs for society and the benefits of avoided climate damages, expressed in present value. For this exercise, different types of climate damages need to be estimated, monetized and aggregated, which is a challenging task and the main research contribution of this strand of literature. The resulting damage functions, however, have been criticized on various grounds – such as for the high level of aggregation, the simplistic coverage of adaptation and catastrophic damages, the distorting effect of using the standard model of discounted utility and other potential shortcomings (see, e.g. Ackerman et al., 2009; Greenstone et al., 2013; Lenton and Ciscar, 2013; Pindyck, 2013). But despite their caveats, these models represent the most comprehensive welfare analysis of different levels of emission control. The most prominent models are DICE, RICE and FUND (see Nordhaus, 2010; Nordhaus and Sztorc, 2013; and Anthoff and Tol, 2013 for the most recent versions).

As noted in section 4.2, CBA-based IAMs trade off the benefits of having higher consumption against the benefits of having less climate damage (often presented as change in production). The implicit price of trading the two goods is the resulting carbon price. More explicitly, these IAMs have been used to estimate the social cost of carbon (SCC), the marginal damage from the change in climate that results from an additional ton of carbon emitted to the atmosphere (Clarkson and Deyes, 2002). The resulting SCC depends on a number of assumptions, such as the projected emissions pathway in the absence of climate policy and the discount rate which, in turn, depends on the rate of pure time preference, the growth rate of per capita consumption, and the elasticity of marginal utility of consumption (cf. Ramsey, 1928).

According to Tol (2013), there are 75 studies on the SCC with 588 different estimates, which reaffirms that the uncertainty is very large, partly because of the different values for the pure rate of time preference. The mean estimate across all studies is a marginal SCC of $196 per metric ton of carbon, although it is driven by some very large estimates. Irrespective of the exact amount, these numbers highlight the fact that the underlying perspective is related to the weak sustainability paradigm which puts forward that the net value of emitting, e.g. for some industrial processes, is higher than the net value of mitigating these emissions. According to Pindyck (2013), however, these numbers suggest “a level of knowledge and precision that is nonexistent”. He not only argues that some of the model inputs (e.g. the rate of pure time preference) are subject to ethical (cf. Stern, 2008) or political decisions; he also highlights the empirical uncertainty of many other model inputs, such as the value of climate uncertainty and the arbitrary nature of the models’ damage functions. Additionally, Stern (2013) argues that the treatment of economic growth is inappropriately represented in the models because they assume an underlying ‘exogenous’ growth rate. However, damages from unabated climate change are likely to reduce the growth rate substantially, so that the assumption of an exogenous growth rate and an exogenous discount rate can no longer be justified. The inherent uncertainties of the climate damages have raised the awareness that the implications of different versions of strong sustainability (e.g. imposing different carbon budgets, concentration or temperature levels) should be explored in terms of impacts, adaptation and mitigation costs and risks. This disaggregated information can facilitate a debate about the costs of action and non-action which is not based on a misleading precision of numbers. In the next section we focus on the mitigation costs of different versions of IAMs reflecting strong sustainability approaches to climate change mitigation.

4.3.1.2 Strong sustainability, delayed participation and limited availability of technologies

The standard approach taken by CEA-based IAMs involves two objectives. One is consumption and it is measured as a continuous variable. This means that any small increase in it increases overall utility. The second objective is an environmental one and it is measured as an all-or-nothing alternative. Achieving, for example, a 450 ppm CO_2-eq concentration target, implies that the objective is reached. A further reduction to 425 ppm does not yield additional utility. Missing the objective is avoided at all cost, effectively attaching a utility of negative infinity to it. As a consequence, the maximization of the model strives to achieve the highest amount of consumption, which still respects the 450 ppm target.

One recent paper (Luderer et al., 2013) is able to clearly show the negative relationship between temperature targets and mitigation costs in a so-called 'temperature–cost trade-off curve' (see Figure 4.2): the lower a specific temperature target, the higher are the associated aggregated mitigation costs for achieving it.[11] Particularly noteworthy is also the highly convex shape of the temperature-cost trade-off curve, which indicates that costs increase disproportionally the lower the long-term temperature target is set. Note should however be taken of the blue shaded bands that exemplify the uncertainty associated with reaching a specific temperature target. This uncertainty relates to a large part to uncertainties about carbon cycle feedbacks and the climate system response to changes in atmospheric GHG concentration. As a consequence, when translating concentration levels into temperature targets, this uncertainty is accounted for by assigning different probabilities to reaching a particular target. Ensuring a higher likelihood of achieving a climate target implies tighter emissions constraints, and thus higher costs (cf. also Rogelj et al., 2013a).

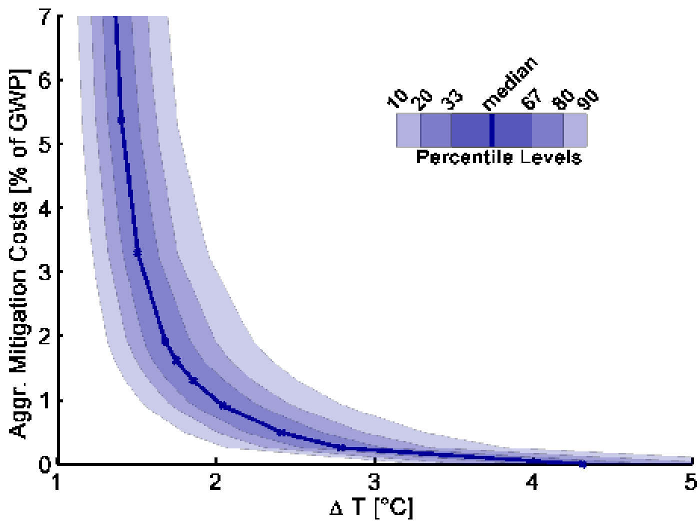

Figure 4.2 Temperature–cost trade-off curve. Note: The figure shows the relationship between maximum twenty-first-century surface air temperature targets and aggregated mitigation costs for a scenario assuming no global climate agreement till 2015 and a default technology portfolio. Blue shaded bands show uncertainty ranges of the climate system's response to anthropogenic activities. Source: Luderer et al. (2013).

[11] Mitigation costs in CEA-based IAMs typically measure efforts related to emissions reductions in comparison to a counterfactual baseline scenario but often do not take into account avoided damages or co-effects of climate change mitigation on other policy objectives (see section 4.3.2.1 for the few existing exceptions). There is a range of ways to report mitigation costs, depending on the model type, the purpose of a particular study (for example model intercomparison exercises) and other reasons. In the figures that are shown here, mitigation costs refer to macroeconomic consumption losses that are aggregated with a 5 percent discount rate over the time horizon 2010–2100 and divided by the aggregated and discounted gross world product (GWP) (see Luderer et al., 2013). Other ways to present mitigation costs relate to: (i) aggregated and discounted increase in energy system costs relative to GDP/GWP; (ii) aggregated and discounted GDP/GWP losses relative to GDP/GWP; (iii) aggregated and discounted consumption losses relative to global consumption; and (iv) 'balanced growth equivalents (BGEs)' (see Anthoff and Tol (2009) for a discussion of the use of BGEs in CBA-based IAMs). While all these indicators can be interpreted as delaying production/consumption growth, BGE can also be interpreted as an exogenous price shock to the global economy.

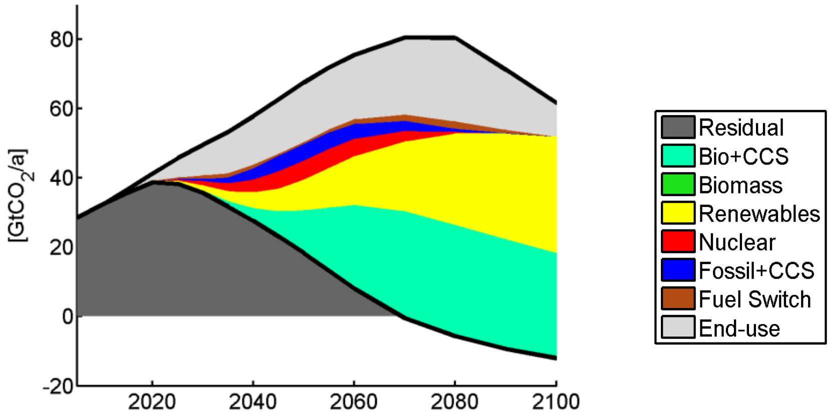

Figure 4.3 Emission gap between the baseline scenario and the climate policy scenario limiting global warming to 2°C with a 67 percent likelihood. Note: The emission reductions induced by climate policy are decomposed into six technology groups as well as the contribution of changes in energy demand. Source: Decomposition analysis based on scenario data from Luderer et al. (2013) and the methodology presented in Luderer et al. (2012b).

Figure 4.3 provides an overview of the contribution of different technology options to the emission reductions required to meet a low stabilization target. As can be seen, different technology groups contribute with varying shares to the emission reductions that are necessary to deviate from a counterfactual baseline scenario (upper black line) to reach a 2°C target with a 67% likelihood (lower black line). In this study, bioenergy use with carbon capture and storage (BECCS), non-biomass renewables, and energy demand reductions play the largest roles (Luderer et al., 2013). The important role of bioenergy can be ascribed to its ability to generate 'negative emissions' (i.e. removing emissions from the atmosphere) when combined with carbon capture and storage (CCS) technologies (Edenhofer et al., 2014).

In a further step, IAMs can investigate the effects of different challenges to achieving such a low stabilization target via introducing additional constraints to the model. Recent research examined, for example, the effects of sub-optimal climate policies (e.g. due to delays in setting up a global climate agreement, cf. Clarke et al., 2009; Jakob et al., 2012; Luderer et al., 2012a, 2016) and limited availability of technologies (Azar et al., 2010; Edenhofer et al., 2010; Tavoni et al., 2012; Kriegler et al., 2013a) on the costs of climate change mitigation or the combined effect (van Vliet et al., 2012; Luderer et al., 2013; Rogelj et al., 2013a, 2013b; Riahi et al., 2015).

The availability of different mitigation technologies was found to have a marked effect on the overall costs of abatement. While leaving nuclear energy out of the technology mix increases abatement costs compared to a full technology scenario only slightly, scenarios in which CCS is assumed not to be available show much higher cost increases for reaching a specific temperature target (Figure 4.4). Also, the unavailability of specific technology options results not only in increasingly higher abatement costs but could make reaching low stabilization targets infeasible in their entirety, in particular if biomass or CCS – which are key ingredients for negative emissions technologies – are limited (Luderer et al., 2013; Riahi et al., 2015; Kriegler et al., 2013a). Such findings are exemplified by the arrows in Figure 4.4, which point to the increase in the lowest achievable mitigation target at a specific mitigation cost level as a consequence of the unavailability of CCS.

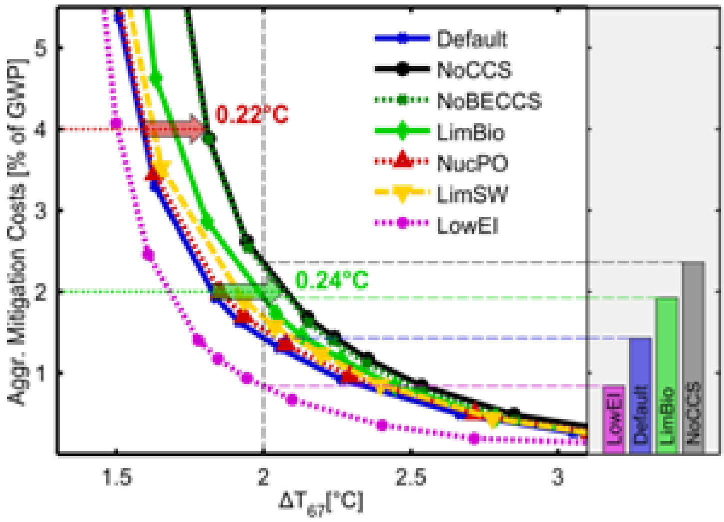

Figure 4.4 Temperature–cost trade-off curves showing the effect of technology availability on aggregated mitigation costs for reaching a specific temperature target (maximum 2010–2100 temperatures reached with a 67 percent likelihood). Notes: Bar charts indicate economic challenges of limiting warming to 2°C. Legend: Default – full technology portfolio; NoCCS – unavailability of CCS; NoBECCS – unavailability of CCS in combination with bioenergy (BECCS); LimBio – reduced bioenergy potential (100 EJ/year compared to 300 EJ/year in all other cases); NucPO – phase out of investments into nuclear energy; LimSW – penetration of solar and wind power limited to 20%; LowEI – lower energy intensity, with final energy demand per economic output decreasing faster than historically observed. Source: Luderer et al. (2013).

A further prerequisite for a cost-efficient transformation pathway is an immediate implementation of climate policies, implying full flexibility in the timing of emission reductions. If climate policies are inexistent or weaker than optimal in the near term, larger emission reductions are required in the medium to long term, making it more difficult and more costly to reach climate targets. Figure 4.5a shows how such delays in ambitious and global cooperation, by keeping the climate policy regime weak and fragmented up to 2015, 2020 and 2030, respectively, are associated with increasingly higher overall climate policy costs. At the same time, such delays also cause a shift in the temperature–cost trade-off curves towards higher temperatures, which means that for certain mitigation cost levels, some temperature targets cannot be met any longer (as indicated by the arrows in the figure). This effect would be aggravated if such delays in global cooperation were to occur in conjunction with the unavailability of certain technology options. In this regard, Figure 4.5b emphasizes the increased dependence on bioenergy for reaching ambitious temperature targets in case of prolonged fragmented global cooperation.

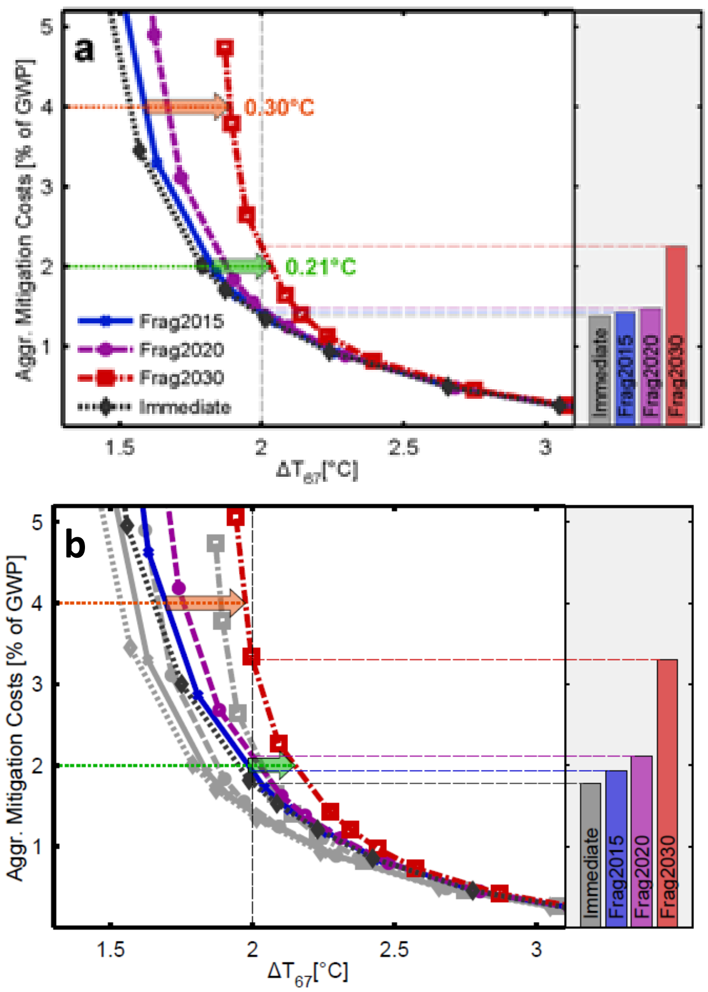

Figure 4.5 Temperature–cost trade-off curves showing (a) the effect of timing of global comprehensive mitigation action and (b) the effect of a limited bioenergy potential on aggregated mitigation costs. Notes: X-axis shows temperature targets (maximum 2010–2100 temperatures) reached with a 67% likelihood. Bar charts indicate economic challenge of limiting warming to 2°C. Frag2015, Frag2020 and Frag2030 scenarios assume that climate policies remain weak and fragmented and without a globally harmonized GHG pricing until 2015, 2020 and 2030, respectively. The hypothetical Immediate scenario assumes global comprehensive emissions reductions effective and implemented from 2015 onwards. Source: Luderer et al. (2013).

4.3.2 Multiple objectives approaches in IAM scenario literature

While the choice of a specific GHG concentration target and its associated costs are defining elements for making a development pathway sustainable or not, other SD concerns also deserve more specific consideration. This is because the deployment of a range of mitigation technologies comes with its own set of sustainability benefits and concerns. For example, the broad-scale application of BECCS, i.e. the application of CCS technologies to bioenergy conversion processes, in order to achieve negative emissions towards the end of the century, may not be compatible with land, water, biodiversity and livelihood concerns (see, e.g. Creutzig et al., 2012a for a broader discussion of SD concerns of bioenergy). Recent developments within the IAM community have shown considerable efforts to include such additional objectives in the models (McCollum et al., 2011; GEA, 2012; PBL, 2012; Howells et al., 2013), for example air quality, public health and energy security (Bollen et al., 2010; McCollum et al., 2013). Exploring the impact of multiple objectives on overall policy costs and mitigation pathways, these studies are able to identify potential synergies and trade-offs between climate change mitigation, energy security and local air pollution goals. This methodological innovation could be a starting point to conceptualize the debate on co-benefits in a consistent SD framework (see, e.g. Edenhofer et al., 2014).

4.3.2.1 The interaction between mitigation, air quality and energy security in recent IAM scenario literature

This section focuses on two recent studies that attempt to quantify the many interactions across mitigation, air quality and energy security in economic terms. The analysis in Bollen et al. (2010) uses a CBA-based IAM and develops a set of scenarios to assess the costs and benefits of pursuing the three objectives in isolation or in various combinations. For each scenario, the model calculates an emission time path that optimizes social welfare which, in turn, depends on the different levels of the three objectives. McCollum et al. (2013) use a CEA-based IAM. Instead of calculating the optimal levels of the three different objectives, they impose constraints to their model that correspond to a set of policy targets of varying stringency for each objective. Based on 624 scenarios, they calculate how to achieve these policy targets in the most cost-effective way, respectively.

Despite the different methodologies, both studies find important synergies across these multiple objectives and highlight the cost savings of policies – particularly in the short term – by addressing these objectives in an integrated manner as opposed to pursuing them in isolation. Many of these synergies materialize through the reduction of energy intensity and energy demand, consequently reducing the need for end-of-pipe pollution control equipment and imported fossil fuels. However, the synergies across stringent climate policies and additional policy objectives will be much less pronounced if future policies for air quality and energy security are more aggressive than currently planned and as assumed in the model runs (Clarke et al., 2014).

4.3.2.2 Energy security in recent IAM scenario literature

Focusing on the particular synergy between mitigation and energy security also allows some interesting insights into the broader implications of some mitigation pathways. Achieving or maintaining energy security constitutes a priority in many national development plans. While recent IAM literature cannot provide sufficient information down to the national level, insights can still be gained for some regional developments under climate policies. Model results show that changes in the energy mix as a response to climate policies are mainly caused by reductions in the volume and intensity of global energy trade, with the effect that under climate policies energy systems of most regions diverge more than under the baseline (Cherp et al., 2016). However, the implications of this development in the diversity of the energy mix can exhibit marked differences across regions (Figure 4.6). In China, where the energy mix in the baseline scenario (BAU) is dominated by coal, it becomes more diversified by the introduction of low-carbon energy technologies in a climate policy scenario (450 ppm CO_2eq). In Africa, fossil fuel-based technologies are largely replaced by biomass and the diversity in the energy mix decreases. These results hint at a change in regional energy mixes towards being a better representation of the regional differences in resource availability and demand dynamics (Cherp et al., 2016).

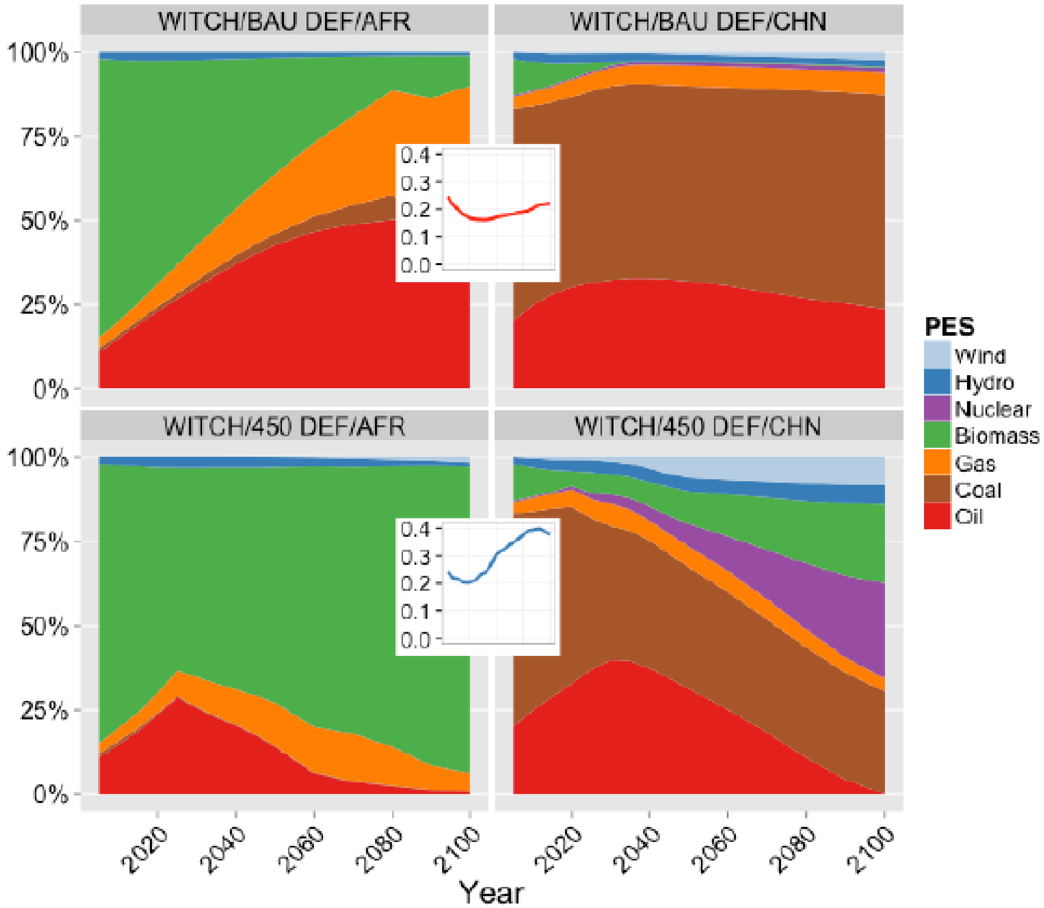

Figure 4.6 Energy mix in Africa (AFR) and China (CHN) and the standard deviation of energy diversity in all the world regions under the Baseline and a 450 scenario in WITCH. Legend: BAU DEF – Baseline default; 450 DEF – 450 ppm default; PES – Total Primary Energy Supply.

Source: Used with permission of Springer Nature, from Cherp et al. (2016) Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Clim. Change*, 136(1), 83–94, Figure S-7.

4.3.2.3 Energy demand for development in recent IAM scenario literature

The advantages of IAMs, however, come with some important caveats, such as the lack of distributional, and limited spatial and temporal resolution, as well as structural rigidity (see Sathaye et al., 2011, section 9.4). For example, CEA-based IAMs often report final energy consumption levels of developing-country households that correspond to minimal poverty thresholds such as 10 GJ per capita (Ekholm et al., 2010; van Ruijven et al., 2011; Daioglu et al., 2012; Krey et al., 2012; Narula et al., 2012). However, these implicit assumptions are often not consistent with reaching more ambitious development levels at the same time – unless it is assumed that the pace of decoupling growth from energy use far exceeds historical trends (Steckel et al., 2013). This is all the more challenging as increased energy prices due to climate policies could delay structural changes and the build-up of physical infrastructure (Jakob and Steckel, 2013; Goldemberg et al., 1985). Taking these issues into account in IAM analyses would increase the plausibility of model results (Steckel et al., 2013; cf. van Ruijven et al., 2008).

4.4 Future challenges for research on mitigation and sustainable development

The link between climate change mitigation and SD is one of the most challenging areas of theoretical and applied sustainability science.

4.4.1 Improved realism in transformation pathways

With their ability to dynamically evaluate the portfolio of mitigation options and thus outline different transformation pathways, IAMs constitute powerful tools in applied sustainability science. However, because of the underlying optimization assumptions, these IAM scenarios exhibit an inherent tendency to overlook real-world imperfections. While recent developments have clearly shown that IAMs are able to incorporate real-world imperfections, more efforts have to be undertaken in order to overcome the biased optimism in these models.

At a sectoral level, path dependencies and lock-in effects have to be taken into account for a more realistic evaluation of the inertia of transformation processes. The installed infrastructure and the limited flexibility of other capital stocks cause additional costs which are not sufficiently reflected in many IAMs. In addition to these more conceptual problems, mitigation efforts in some sectors entail synergies and trade-offs which only become visible when case studies and more sector-specific studies are included in a more comprehensive analysis. For example, the impact of large-scale bioenergy use on food security, biodiversity, water infrastructure and livelihoods is a contentious example where a dialogue between different communities is required to arrive at a more comprehensive picture that is useful for decision-makers (see Searchinger et al., 2009; Chum et al., 2011; Creutzig et al., 2012a, b; Edenhofer et al., 2013a; Kriegler et al., 2013b; Tavoni and Socolow, 2013). Integrating evidence across different research communities operating at different scales would be an important contribution to improve the understanding of transformation pathways.

At the regional level, assumptions about the potential for development in climate stabilization scenarios might also be perceived as optimistic, and development economists investigate how rapid reductions of energy demand might create potential poverty traps or limit the potential for further economic growth, particularly in developing countries (see Steckel et al., 2013). In addition, the existence of fat tails needs to be considered not only in the context of climate damages but also in the analysis of risky mitigation for developing countries. A very promising research avenue will be to incorporate non-standard tools of risk management into IAMs (for a discussion, see Kunreuther et al., 2013).

At the institutional level, an additional future challenge for IAMs will be to implement the whole range of policy instruments available to policymakers at different government levels such as municipalities, states and national governments (Edenhofer et al., 2013b). It would be highly valuable if the interaction between these government levels were represented explicitly, for example to arrive at an understanding of how and when national carbon taxes might improve the likelihood for international cooperation. Since nation states are often embedded in a situation of tax competition, another interesting future research direction might explore the impact of tax competition for the likelihood of international cooperation (Edenhofer et al., 2013b). Admittedly, some IAMs have been able to incorporate a game-theoretic structure which allows analyzing the impact of policy instruments on international cooperation (e.g. coordinated R&D investments, international spillovers). While this can be perceived as a promising starting point, more can and should be done in this direction.

4.4.2 Population policy and life-style changes

Population dynamics and mitigation is a relatively unexplored area and at present all IAMs include exogenous population scenarios. However, modeling comparison exercises that have carried out sensitivity analyses of high and low population scenarios are relatively rare (Kriegler et al., 2013c). This remains an important avenue for future research. Differences in population levels may have large effects beyond the decarbonization of the electricity sector. GHG emissions in the agricultural sector in particular might strongly depend on population. Understanding this topic requires a comprehensive investigation of land-use dynamics, which might turn out to be quite challenging to transform. As a consequence, more detailed studies are needed to improve our understanding of the link between the energy and the land-use system (Calvin et al., 2016).

Considering population dynamics endogenously becomes even more challenging. Millner (2013) points out that the standard welfare functions, average utilitarianism and classical utilitarianism, fail to fulfil some elementary axioms. Based on Blackorby et al. (2005) Millner proposes using critical level utilitarianism instead since it performs much better on these axioms. Within this normative framework, population policy can be evaluated. At a descriptive level, the fertility decision of families is endogenized in overlapping generation models, see Galor (2011). These decisions might become sub-optimal when social security schemes are absent, underinvestment in education is persistent or other intertemporal market imperfections are considered explicitly. It is needless to say that the proposed policy instruments ranging from social security schemes, incentives for investment in human capital, legal allowances for a specific number of children, contraception and abortion are highly contested. While welfare economics is not in a position to resolve these highly contested ethical issues, IAMs are able to explore some impacts of different social welfare functions on population and mitigation policies.

It is obvious that lifestyle changes might impact GDP. From a welfare-theoretic point of view it is still debated how lifestyle changes can be conceptualized. There are many reasons why people might have preferences for a less growth-intensive lifestyle: the interest in more leisure time when material well-being is increasing; the preference for more non-material goods like investment in social capital, relationship to friends, less-intensive status consumption; and higher preferences for 'green' goods and technologies. However, there is an ongoing debate about the empirical validity and the theoretical plausibility of these aspects (see Frey, 2008).

One explicit link between IAMs and SD exists in studies on 'Low-Carbon Society (LCS) pathways' which typically include actions that are compatible with SD principles and contribute to the stabilization of GHG concentration to avoid dangerous climate change (e.g. Skea and Nishioka, 2008; Kainuma et al., 2012; Hourcade and Crassous, 2008). In contrast to conventional low-carbon scenarios, which tend to rely on carbon pricing to achieve system-wide transformations, LCS pathways typically assume policies and measures that facilitate lifestyle changes, green manufacturing processes, and investments into energy-efficient devices, recycling measures and other targeted technologies (Shukla and Chaturvedi, 2012). As particular attention is paid to local conditions and short-term needs and objectives, the existing literature is regional in focus (Kainuma et al., 2012). One finding from the Indian context might be relevant globally though: the sustainability scenario was shown to feature a lower carbon price compared to the one delivering identical mitigation in the conventional mitigation scenario (Shukla et al., 2008). Including a broader set of objectives, such as distributional aspects and lifestyle changes with, e.g. preferences for green technologies, can thus provide interesting insights into the relevance of different mitigation measures and options when the whole solution space is considered (see Figure 4.1).

4.5 Concluding remarks

This chapter has tried to summarize recent efforts in research to embed climate change mitigation in the narrative of SD. For an improved understanding how research on climate change mitigation is linked to sustainable development, this chapter referred to SD as a narrative including inter- and intragenerational justice, a lens to look at the interconnections between the economy, society and the environment to support future and long-term human well-being as well as a multi-objective framework to guide public policy to address currently existing externalities. The chapter showed how research on climate change mitigation is linked to sustainable development by introducing a simple conceptual framework and by presenting two categories of IAMs – an important tool of applied sustainability research. Against this background, an explicit analysis of management strategies for decisionmakers confronted with catastrophic risks, tipping points and non-linearities in mitigation and adaptation will need to become a key topic in future sustainability research. This research can help facilitate a public discourse about and guide public policy choices between the trade-offs and synergies across different SD objectives.

4.6 References

Ackerman F., DeCanio, S.J., Howarth, R. and Sheeran, K. (2009), 'Limitations of integrated assessment models of climate change', *Climatic Change*, **95**, 297–315.

Anthoff, D. and Tol, R.S. (2009), 'The impact of climate change on the balanced growth equivalent: An application of FUND', *Environmental and Resource Economics*, **43**(3), 351–67.

Anthoff, D. and Tol, R.S.J. (2013), '*The uncertainty about the social cost of carbon: A decomposition analysis using FUND', Climatic Change*, **117**(3), 515–30.

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D.P., den Elzen, K.M.G.J., Möllersten, K. and Larson, E.D. (2010), 'The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS)', *Climatic Change*, **100**, 195–202.

Blackorby, C., Bossert, W. and Donaldson, D.J. (2005), *Population Issues in Social Choice Theory, Welfare Economics, and Ethics*, Cambridge: Cambridge University Press.

Bollen, J., Hers, S. and van der Zwaan, B. (2010), 'An integrated assessment of climate change, air pollution, and energy security policy', *Energy Policy*, **38**, 4021–30.

Calvin, K., Wise, M., Luckow, P., Kyle, P., Clarke, L. and Edmonds, J. (2016), 'Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions', *Climatic Change*, **136**, 57–68.

Cherp, A., Jewell, J., Vinichenko, V., Bauer, N. and DeCian, E. (2016), 'Global energy security in long-term scenarios under different climate policies, GDP growth and fossil fuel availability assumptions', *Climatic Change*, **136**, 83–94.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H. and Gabrielle, B. (2011), 'Bioenergy', in: Edenhofer, O. et al. (eds), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge, UK and New York: Cambridge University Press.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S. and Tavoni, M. (2009), 'International climate policy architectures: Overview of the EMF 22 International scenarios', *Energy Economics*, **1**(31), 64–81.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B., van Vuuren, D.P. (2014), 'Assessing Transformation Pathways', in: Edenhofer, O. et al. (eds), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

Clarkson, R. and Deyes, K. (2002), *Estimating the Social Cost of Carbon Emissions*, London: Department of Environment, Food and Rural Affairs.

Creutzig, F., von Stechow, C., Klein, D., Hunsberger, C., Bauer, N., Popp, A. and Edenhofer, O. (2012a), 'Can bioenergy assessments deliver?', *Economics of Energy & Environmental Policy*, **1**(2), 65–82.

Creutzig, F., Popp, A., Plevin, R., Luderer, G., Minx, J. and Edenhofer, O. (2012b), 'Reconciling top-down and bottom-up modeling on future bioenergy deployment', *Nature Climate Change*, **2**, 320–27.

Daioglou, V., van Ruijven, B.J. and van Vuuren, D.P. (2012), 'Model projections for household energy use in developing countries', *Energy*, **37**, 601–15.

Dubash, N.K., Raghunandan, D., Sant, G. and Sreenivas, A. (2013), 'Indian climate change policy exploring a co-benefits based approach', *Economic & Political Weekly*, **xlviii**(22), 47–61.

Edenhofer, O. and Flachsland, C. (2012), 'Transforming the global energy system: Pathways towards a sustainable energy supply', in: Debiel, T., Hippler, J., Roth, M. and Ulbert, C. (eds), *Global Trends 2013: Peace – Development – Environment*, Bonn: Stiftung Entwicklung und Frieden (SEF).

Edenhofer, O., Seyboth, K., Creutzig, F. and Schlömer, S. (2013a), 'On the sustainability of renewable energy sources', *Annual Review of Environment Resources*, **38**, 16.1–16.32.

Edenhofer, O., Flachsland, C., Jakob, M. and Lessmann, K. (2013b), 'The atmosphere as a global commons: challenges for international cooperation and governance', Discussion Paper 2013-58, Harvard Project on Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School, August.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M. and Köhler, J. (2006), 'Induced technological change: Exploring its implications for the economics of atmospheric stabilization: Synthesis report from the innovation modeling comparison project', *The Energy Journal*, **27**(Special Issue 1), 57–107.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, S., Turton, H. and van Vuuren, D.P. (2010), 'The economics of low stabilization: Model comparison of mitigation strategies and costs', *Energy Journal*, **31**, 11–48.

Edenhofer O. et al. (2014), 'Technical summary', in: Edenhofer, O. et al. (eds), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

Ekholm, T., Krey, V., Pachauri, S. and Riahi, K. (2010), 'Determinants of household energy consumption in India', *Energy Policy*, **38**, 5696–707.

Ekins, P. (2014), 'Strong Sustainability and Critical Natural Capital', in: Atkinson, G., Dietz, S., Neumayer, E., Agarwala, M. (Eds.), *Handbook of Sustainable Development*, 2nd edn, Cheltenham, UK: Edward Elgar.

Fischedick, M., Schaeffer, R., Adedoyin, A., Akai, M., Bruckner, T., Clarke, L., Krey, V., Savolainen, I., Teske, S., Ürge-Vorsatz, D. and Wright, R. (2011), 'Mitigation potential and costs', in Edenhofer, O. et al. (eds), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge, UK and New York: Cambridge University Press.

Fleurbaey, M. (2009), 'Beyond GDP: The quest for a measure of social welfare', *Journal of Economic Literature*, **47**(4), 1029–75.

Frey, B.S. (2008), *Happiness: A Revolution in Economics*, Cambridge, MA: MIT Press.

Fukuda-Parr, S. (2012), 'Should global goal setting continue, and how, in the post-2015 era?', *DESA Working Paper* No. 117, available at: www.un.org/esa/desa/papers/2012/wp117_2012.pdf.

Galor, O. (2011), *Unified Growth Theory*, Princeton, NJ: Princeton University Press.

GEA (2012), *Global Energy Assessment: Toward a Sustainable Future*, Cambridge: Cambridge University Press and Laxenburg: International Institute for Applied Systems Analysis.

Goldemberg, J., Johansson, T.B., Reddy, A.K.N. and Williams, R.H. (1985), 'Basic needs and much more with one kilowatt per capita', *Ambio*, **14**(4/5), 190–200.

Gollier, C. (2012), *Pricing the Planet's Future: The Economics of Discounting in an Uncertain World*, Princeton, NJ: Princeton University Press.

Greenstone, M., Kopits, E. and Wolverton, A. (2013), 'Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation', *Review of Environmental Economics and Policy*, **7**, 23–46.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N. and Noble, I. (2013), 'Sustainable development goals for people and planet', *Nature*, **495**, 305–307.

Hepburn, C. and G. Gosnell (2014), Evaluating Impacts in the Distant Future: 'Cost-benefit Analyses, Discounting, and the Alternatives', in: Atkinson, G., Dietz, S., Neumayer, E., Agarwala, M. (Eds.), *Handbook of Sustainable Development*, 2nd edn, Cheltenham, UK: Edward Elgar.

Hourcade, J.C. and Crassous, R. (2008), 'Low-carbon societies: A challenging transition for an attractive future', *Climate Policy*, **8**(6), 607–12.

Hourcade, J-C., Jaccard, M., Bataille, C. and Ghersi, F. (2006), 'Hybrid modeling: New answers to old challenges – Introduction to the Special Issue of The Energy Journal', *Energy Journal*, **27**(Special Issue October), 1–12.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., van Velthuizen, H., Wiberg, D., Young, C., Roehrl, R.A., Mueller, A., Steduto, P. and Ramma, I. (2013), 'Integrated analysis of climate change, land-use, energy and water strategies', *Nature Climate Change*, **3**, 621–6.

IPCC (2007), *Climate Change 2007: Mitigation of Climate Change*. *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds), Cambridge: Cambridge University Press.

Jakob, M. and Steckel, J. (2014), 'How climate change mitigation could harm development in poor countries', *WIREs Climate Change*, **5**(2), 161-8.

Jakob, M., Luderer, G., Steckel, J., Tavoni, M. and Monjon, S. (2012), 'Time to act now? Assessing the costs of delaying climate measures and benefits of early action', *Climatic Change*, **114**, 79–99.

Kainuma, M., Shukla, P.R. and Jiang, K. (2012), 'Framing and modeling of a low carbon society: An overview', *Energy Economics*, **34**(Sup3), S316–S324.

Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Cariño Olvera, M., Fullerton, D., Gollier, C., Hanemann, W.M., Hassan, R., Jotzo, F., Khan, M.R., Meyer, L., Mundaca, L. (2014), 'Social, Economic and Ethical Concepts and Methods', in: Edenhofer, O. et al. (eds), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

Krey, V., O'Neill, B.C., van Ruijven, B., Chaturvedi, V., Daioglou, V., Eom, J., Jiang, L., Nagai, Y., Pachauri, S. and Ren, X. (2012), 'Urban and rural energy use and carbon dioxide emissions in Asia', *Energy Economics*, **34**, S272–S283.

Kriegler, E., Weyant, J.P., Blanford, J.P., Clarke, L., Edmonds, J., Fawcett, A., Krey, V., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M. and van Vuuren, D.P. (2013a), 'The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies', *Climatic Change*, **123**(3-4), 353–367.

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G. and Klein, D. (2013b), 'Is atmospheric carbon dioxide removal a game changer for climate change mitigation?', *Climatic Change*, **118**, 45–57.

Kriegler, E., Mouratiadou, I., Luderer, G., Bauer, B., Calvin, K., DeCian, E., Brecha, R., Chen, W., Cherp, A., Jiang, K., Pachauri, S., Sferra, F., Tavoni, M., Edenhofer, O. and Edmonds, J. (2013c), 'Roadmaps towards sustainable energy futures and climate protection: A synthesis of results from the RoSE project', available at: http://ampere-project.eu/web/images/Presse/ampere_newsletter_2.pdf.

Krupnick, A., Dallas, B. and Markandya, A. (2000), 'The ancillary benefits of climate change mitigation: A conceptual framework', in: OECD (ed.), *Ancillary Benefits and Costs of Greenhouse Gas Mitigation*, Proceedings of an IPCC co-sponsored workshop, March, Washington DC, pp. 53–93.

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C.B. and Yohe, G. (2013), 'Risk management and climate change', *Nature Climate Change*, **3**(5), 447–50.

Lenton, T.M. and Ciscar, J-C. (2013), 'Integrating tipping points into climate impact assessments', *Climatic Change*, **117**(3), 585–97.

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J.C., Waisman, H. and Edenhofer, O. (2012a), 'The economics of decarbonizing the energy system: Results and insights from the RECIPE model intercomparison', *Climatic Change*, **114**, 9–37.

Luderer, G., Pietzcker, R., Kriegler, E., Haller, M. and Bauer, N. (2012b), 'Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R', *Energy Economics*, **34**, Supplement 3, S378–S390.

Luderer, G., Pietzcker, R.C., Bertram, C., Kriegler, E., Meinshausen, M. and Edenhofer, O. (2013), 'Economic mitigation challenges: How further delay closes the door for achieving climate targets', *Environmental Research Letters*, **8**(3), 034033.

Luderer, G., Bertram, C., Calvin, K., DeCian, E. and Kriegler, E. (2016), 'Implications of weak near-term climate policies on long-term climate mitigation pathways', *Climatic Change*, **136**, 127–140.

McCollum, D., Krey, V. and Riahi, K. (2011), 'An integrated approach to energy sustainability', *Nature Climate Change*, **1**, 428–9.

McCollum, D., Krey, V., Riahi, K., Kolp, P., Grubler, A., Makowski, M. and Nakicenovic, N. (2013), 'Climate policies can help resolve energy security and air pollution challenges', *Climatic Change*, **119**(2), 479–94.

Millner, A. (2013), 'On welfare frameworks and catastrophic climate risks', *Journal of Environmental Economics and Management*, **65**(2), 310–25.

Narula, K., Nagai, Y. and Pachauri, S. (2012), 'The role of decentralized distributed generation in achieving universal rural electrification in South Asia by 2030', *Energy Policy*, **47**, 345–57.

Neumayer, E. (2003), *Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*, 2nd edn, Cheltenham, UK and Northampton, MA, USA: Edward Elgar.

Nordhaus, W.D. (2010), 'Economic aspects of global warming in a post-Copenhagen environment', *Proceedings of the National Academy of Science*, **107**(26), 11721–6.

Nordhaus, W. and Sztorc, P. (2013), 'DICE 2013R: Introduction and User's Manual', 2nd edn, available at: www.econ.yale.edu/~nordhaus/homepage/documents/DICE2013R_Manual_2ndEd.pdf.

PBL (2012), *Roads from Rio+20: Pathways to Achieve Global Sustainability Goals by 2050*, The Hague: Netherlands Environmental Assessment Agency (PBL).

Perman, R., Ma, Y. and McGilvray, J. (1996), *Natural Resource and Environmental Economics*, London: Longman.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M.R. and Wilson, C. (2013), 'The challenge to keep global warming below 2°C', *Nature Climate Change*, **3**, 4–6.

Pindyck, R. (2013), 'Climate change policy: What do the models tell us?', *Journal of Economic Literature*, **51**(3), 860–72.

Ramsey, F.P. (1928), 'A mathematical theory of saving', *The Economic Journal*, **38**, 543–59.

Randal, A. (2014), ‘Weak Sustainability, Conservation, and Precaution’, in: Atkinson, G., Dietz, S., Neumayer, E., Agarwala, M. (Eds.), *Handbook of Sustainable Development*, 2nd edn, Cheltenham, UK: Edward Elgar.

Rao, S., Chirkov, V., Dentener, F., van Dingenen, R., Pachauri, S., Purohit, P., Amann, M., Heyes, C., Kinney, P., Kolp, P., Klimont, Z., Riahi, K. and Schoepp, W. (2012), ‘Environmental modeling and methods for estimation of the global health impacts of air pollution’, *Environmental Modeling & Assessment*, **17**, 613–22.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P. and Kainuma, M. (2015), ‘Locked into Copenhagen pledges: Implications of short-term emission targets for the cost and feasibility of long-term climate goals’, *Technological Forecasting and Social Change*, Part **90** A, 8–23.

Rogelj, J., McCollum, D.L., Reisinger, A., Meinshausen, M. and Riahi, K. (2013a), ‘Probabilistic cost estimates for climate change mitigation’, *Nature*, **493**, 79–83.

Rogelj, J., McCollum, D.L., O’Neill, B.C. and Riahi, K. (2013b), ‘2020 emissions levels required to limit warming to below 2°C’, *Nature Climate Change* **4**, 405–412.

Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., Heath, G., Kadner, S., Mirza, M., Rudnick, H., Schlaepfer, A. and Shmakin, A. (2011), ‘Renewable energy in the context of sustainable development’, in: Edenhofer, O. et al. (eds), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge and New York: Cambridge University Press.

Searchinger, T., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Robertson, P., Schlesinger, W.H. and Tilmaet, G.D. (2009), ‘Fixing a critical climate accounting error’, *Science*, **326**(5952), 527–8.

Shukla, P.R. and Chaturvedi, V. (2012), ‘Low carbon and clean energy scenarios for India: Analysis of targets approach’, *Energy Economics*, **34**, S487–S495.

Shukla, P.R., Dhar, S. and Mahapatra, D. (2008), ‘Low-carbon society scenarios for India’, *Climate Policy*, **8**(sup1), S156–S176.

Skea, J. and Nishioka, S. (2008), ‘Policies and practices for a low-carbon society’, *Climate Policy*, **8**(sup1), S5–S16.

Smith, K.R., Jerrett, M., Anderson, H.R., Burnett, R.T., Stone, V., Derwent, R., Atkinson, R. W., Cohen, A., Shonkoff, S.B., Krewski, D., Pope III, C.A., Thun, M.J. and Thurston, G. (2009), ‘Public health benefits of strategies to reduce greenhouse-gas emissions: Health implications of short-lived greenhouse pollutants’, *The Lancet*, **374**(9707), 2091–103.

Steckel, J.C., Brecha, R.J., Jakob, M., Strefler, J. and Luderer, G. (2013), ‘Development without energy? Assessing future scenarios of energy consumption in developing countries’, *Ecological Economics*, **90**, 53–67.

Stern, N. (2008), ‘The economics of climate change’, *American Economic Review*, **98**(2), 1–37.

Stern, N. (2013), ‘The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models’, *Journal of Economic Literature*, **51**(3), 838–59.

Stocker, T.F. et al. (2013), ‘Summary for Policymakers’, in: Stocker, T.F. et al. (eds), *Climate Change 2013: The Physical Science Basis*, *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.

Tavoni, M. and Socolow, R. (2013), 'Modeling meets science and technology: An introduction to a special issue on negative emissions', *Climatic Change*, **118**(1), 1–14.
Tavoni, M., DeCian, E., Luderer, G., Steckel, J. and Waisman, H. (2012), 'The value of technology and of its evolution towards a low carbon economy', *Climatic Change*, **114**, 39–57.
Tol, R.S.J. (2013), 'Targets for global climate policy: An overview', *Journal of Economic Dynamics and Control*, **37**, 911–37.
UNEP (2012), *The Emissions Gap Report 2012*, Nairobi: United Nations Environment Programme (UNEP).
UNFCCC (1992), 'United Nations Framework Convention on Climate Change (UNFCCC)', FCCC/INFORMAL/84, Bonn, Germany, available at: http://unfccc.int/resource/docs/convkp/conveng.pdf.
UNFCCC (2010), 'The Cancun Agreements', Decision 1/CP.16 FCCC/CP/2010/7/Add. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, available at: http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf#page=2
van Ruijven, B., Urban, F., Benders, R.M.J., Moll, H.C., van der Sluijs, J.P., de Vries, B. and van Vuuren, D.P. (2008), 'Modeling energy and development: An evaluation of models and concepts', *World Development*, **36**(12), 2801–21.
van Ruijven, B.J., van Vuuren, D.P., de Vries, H.J.M., Isaac, M., van der Sluijs, J.P., Lucas, P.L. and Balachandra, P. (2011), 'Model projections for household energy use in India', *Energy Policy*, **39**, 7747–61.
van Vliet, J., van den Berg, M., Schaeffer, M., van Vuuren, D., den Elzen, M., Hof, A., Mendoza Beltran, A. and Meinshausen, M. (2012), 'Copenhagen Accord pledges imply higher costs for staying below 2°C warming', *Climatic Change*, **113**, 551–61.
van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E. and Kram, T. (2009), 'Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials', *Energy Policy*, **37**(12), 5125–39.
WCED (1987), *Our Common Future, From One Earth to One World* (Brundtland Report), Oslo: United Nations World Commission on Environment and Development.
Weitzman, M. (2000), 'The linearised Hamiltonian as comprehensive NDP', *Environment and Development Economics*, **5**(1), 55–68.
Weitzman, M. (2003), *Income, Wealth, and the Maximum Principle*, Cambridge, MA: Harvard University Press.
Weitzman, M.L. (2009), 'On modeling and interpreting the economics of catastrophic climate change', *The Review of Economics and Statistics*, **91**(1), 1–19.
Weitzman, M. (2012), 'GHG targets as insurance against catastrophic climate damages', *Journal of Public Economic Theory*, **14**, 221–44.

5 Integrating global climate change mitigation goals with other sustainability objectives: A synthesis

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Keywords

Welfare-theoretical framework, multiple objectives, co-benefits, air quality, energy security, energy efficiency, energy demand reduction

Abstract

Achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals. This article reviews and synthesizes results from disparate strands of literature on the co-effects of mitigation to inform climate policy choices at different governance levels. The literature documents many potential co-benefits of mitigation for non-climate objectives, such as human health and energy security, but little is known about their overall welfare implications. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives. The incommensurability and uncertainties around the quantification of co-effects become, however, increasingly pervasive the more the perspective shifts from sectoral and local to economy wide and global, the more objectives are analyzed, and the more the results are expressed in economic rather than non-monetary terms. Different strings of evidence highlight the role and importance of energy demand reductions for realizing synergies across multiple sustainability objectives.

5.1 Introduction

A large body of literature has looked at the challenge of meeting stringent climate targets (1–6). However, many argue that stringent climate change mitigation goals are a necessary but insufficient condition for a sustainable energy transition (7–9). Other key sustainability objectives include improved air quality and health, the provision of affordable energy services for all, energy and food security, as well as minimizing energy-related land and water use and biodiversity loss. Mitigation efforts should hence be assessed in a multi-objective framework (8–12), which would need to consider the energy transition as a multilevel governance challenge. On the one hand, mitigation is a global commons problem that warrants a coordinated global response (13, 14). In fact, the integrated model literature has shown that achieving particular mitigation goals, such as the 2°C target, is most cost-effective if approached from a global perspective and results in high long-term global benefits at considerable short-term costs (15, 16). On the other hand, most climate policies are increasingly formulated at national and even subnational levels, where many of the non-climate objectives are often more salient as policy drivers (17–19). Because co-benefits of mitigation hold the prospect of helping achieve some of these other objectives and reducing the short-term costs of climate policies that accrue on the local/national level, the concept has recently attracted increasing attention. Hence, tailored information on the interactions of mitigation and other sustainability objectives is required to guide choices within a multilevel governance framework ranging from the global to the national and subnational levels.

The *Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report* (WGIII AR5) (20), based on the assessment of global integrated model results, highlights that there is no single preferred mitigation pathway for cost-effectively meeting any specific temperature goal. Instead, it indicates that there is flexibility in how a particular mitigation goal can be achieved: The timing of greenhouse gas (GHG) emissions reductions, the choice of particular sets of low-carbon energy supply technologies and their upscaling requirements, etc., can substantially differ across scenarios, both globally and locally (1). Policymakers can increase the level of flexibility by enacting policies that help reduce energy demand (5, 21) and can harness this flexibility by choosing climate policies according to national/local circumstances and preferences. These include the levels of socioeconomic and technological development, distributional aspects, risk perceptions, and priority settings for non-climate objectives (7, 19, 22).

Although there is a wealth of relevant literature on synergies and trade-offs across mitigation and non-climate objectives, evidence remains scattered across different sectoral studies, different research communities, and different scales of analysis. This makes it generally inaccessible for decision making. As with the rapid expansion of literature in climate science in general, there is not enough meaningful interpretation of the sum of the individual sets of results (23; see also 24–26 for bioenergy research). Indeed, the benefits of integrating sectoral evidence with evidence from scenario studies have been highlighted in recent reviews (24, 27–30). Such an integrated perspective is highly relevant for decision making because it advances the understanding of the practical implications of alternative climate policy choices for other human and policy dimensions (8–10, 31).

In this article, we try to connect relevant strings of evidence (scattered across many different strands of literature and different scales of analysis) on the interactions between mitigation and other sustainability objectives. By doing so, we generate new insights and identify robust evidence for policy makers—even for those locations for which no scientific evidence is directly available. This article focuses on a global perspective, aiming to provide insights on the interactions of mitigation and non-climate objectives relevant for understanding the global energy transition challenges.[12] The WGIII AR5 has already made important progress in assessing this broad body of literature by (a) providing both a social welfare and a sustainable development (SD) framework for climate policies in a multi-objective context, (b) assessing the literature on co-effects of mitigation measures in different sectors, and (c) assessing the integrated model literature on co-effects of mitigation pathways on a global scale. It has, however, only provided a limited synthesis, which is divided across several chapters of the report. This has hindered a comprehensive view with more far-reaching insights on this important topic. We further condense and expand the synthesis of the material by (a) presenting the different WGIII AR5 chapters' results at a single glance (see the tables in Sections 5.3 and 5.4.1 below), (b) analyzing the challenges of quantitative aggregation of co-effects, particularly on a global scale, (c) presenting a way forward to usefully draw on existing strings of evidence, (d) discussing the high-level insights gained, and (e) pointing to a promising research agenda for multi-objective literature and its synthesis.

To that end, Section 5.2 provides a welfare-theoretical framework that serves as an organizational device for the review and condensation of sectoral research results in Section 5.3 and of integrated model literature results in Section 5.4. These sections discuss the various aspects focused on by different communities in their analysis of the interactions of mitigation and multiple other sustainability objectives, pointing to their respective strengths as well as the caveats for quantitative synthesis. Section 5.4.3 critically discusses the extent to which integrated models are actually able to assess changes in welfare, and Section 5.5 suggests one possible way forward to make multi-objective implications of climate policy choices more transparent by drawing on the respective strengths of these different communities. Although this approach does not eradicate the incommensurability in the aggregation of various co-effects, particularly on a global scale, it deals with the uncertainties of different sets of results in a more transparent way. It also makes them more accessible to decision makers who would like to understand how to maximize synergies and minimize trade-offs across multiple sustainability objectives.

[12] In practice, the stated rationale of a particular climate policy at the national or local level may not be restricted to mitigation and may be different in varied contexts. In fact, mitigation is often considered the co-benefit of other policies primarily aimed at environmental, health, and development issues (32). The aim of this article is, however, less to illuminate the different drivers of implementing mitigation-related policies at the national or local level but instead to synthesize existing evidence on the global implications for multiple sustainability objectives and social welfare if governments embark on alternative global mitigation pathways.

5.2 A conceptual framework for assessing the co-effects of mitigation

Despite a long-standing interest in the co-effects of mitigation (see, e.g., 33), there is no commonly agreed upon terminology. For example, positive (negative) co-effects are referred to in the literature as co-benefits or ancillary benefits (co-costs, ancillary costs, adverse side effects or trade-offs), but these terms have been defined differently across studies (see 12 for a review). This is largely because the same terms have been used to describe a range of effects from different methodological approaches. Box 5.1 introduces a conceptual welfare-theoretical framework. We use this framework as a device for structuring our literature review and condensation of insights from different strands of literature.

Box 5.1. A conceptual welfare-theoretic framework for assessing the co-effects of mitigation

Suppose social welfare W can be written as a function of different objectives z_i ($i = 1, \ldots, m$); the attainment of each of those objectives is influenced by the deployment of a number of technological or other measures m_k ($k = 1, \ldots, n$) which, in turn, are influenced by the implementation of a number of policies, p_l ($l = 1, \ldots, o$). Now consider a marginal change dp_l in one or more policies. Building on the conceptual framework presented by Kolstad et al. (34), but highlighting the important role of the broad set of measures through which policies often impact objectives, the net effect on social welfare effect is given by Equation 1.[13]

$$dW = \sum_{i=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{o} \frac{\partial W}{\partial z_i} \frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l} dp_l \qquad 1.$$

Based on these considerations, we define co-benefits (or adverse side effects) as the potential positive (or negative) effects of a policy p_l aimed at one objective on other objectives ($\frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l}$ for $\mathrm{l} \neq \mathrm{i}$), without evaluating the implications for social welfare (not multiplied by $\partial W / \partial \mathrm{z_i}$, i.e. the value different individuals or society as a whole attach to the co-effect). This differentiation between the non-monetary effect on a particular objective and the associated social welfare effect is important because the overall magnitude is determined by the two effects in combination, which may also work in different directions (see Section 5.4.3). Moreover, co-effects are often reported in non-monetary or even qualitative terms only because they are challenging to measure, quantify, and monetize because of a variety of practical obstacles, such as data availability (see, e.g., 12, 35, 36).

We classify the literature into three main strands based on this framework. Figure 5.1 provides an overview and relates the strands to each other. Most importantly, it highlights that the system boundaries of the strands are very different. System boundary

[13] Please note that spatial, temporal and distributional dimensions have been omitted from Equation 1, although they are discussed where relevant. A discussion of changing governance conditions is beyond the scope of this article.

expansion from strand 1 to 3 is paved with complexities and practical problems, which explains the increasingly thin literature base.

Literature strand 1 (from climate change mitigation measures to multiple objectives; see I in Figure 5.1) links mitigation measures, defined here as "technologies, processes and practices that contribute to mitigation" (37, p. 1266), to other sustainability objectives z_i $(i = 1, \ldots, m)$. In particular, it characterizes these mitigation measures in terms of their multiple co-benefits and adverse side effects on non-climate objectives (see Section 5.3), mostly in the context of specific sectors/ applications and locations. Other co-effects accrue to stakeholders outside the sector/location (upstream, downstream, or downwind). Such evidence can inform the technological choices of national and local policy makers by highlighting the potential co-effects of mitigation measures for other objectives. This task remains challenging, however, because the wealth of evidence is scattered across multiple research communities and studies, each dealing with specific aspects, sectors, locations, and sometimes policies, but neglecting cross sectoral and cross regional interactions of policies, technology choices, and the associated implications for social welfare.

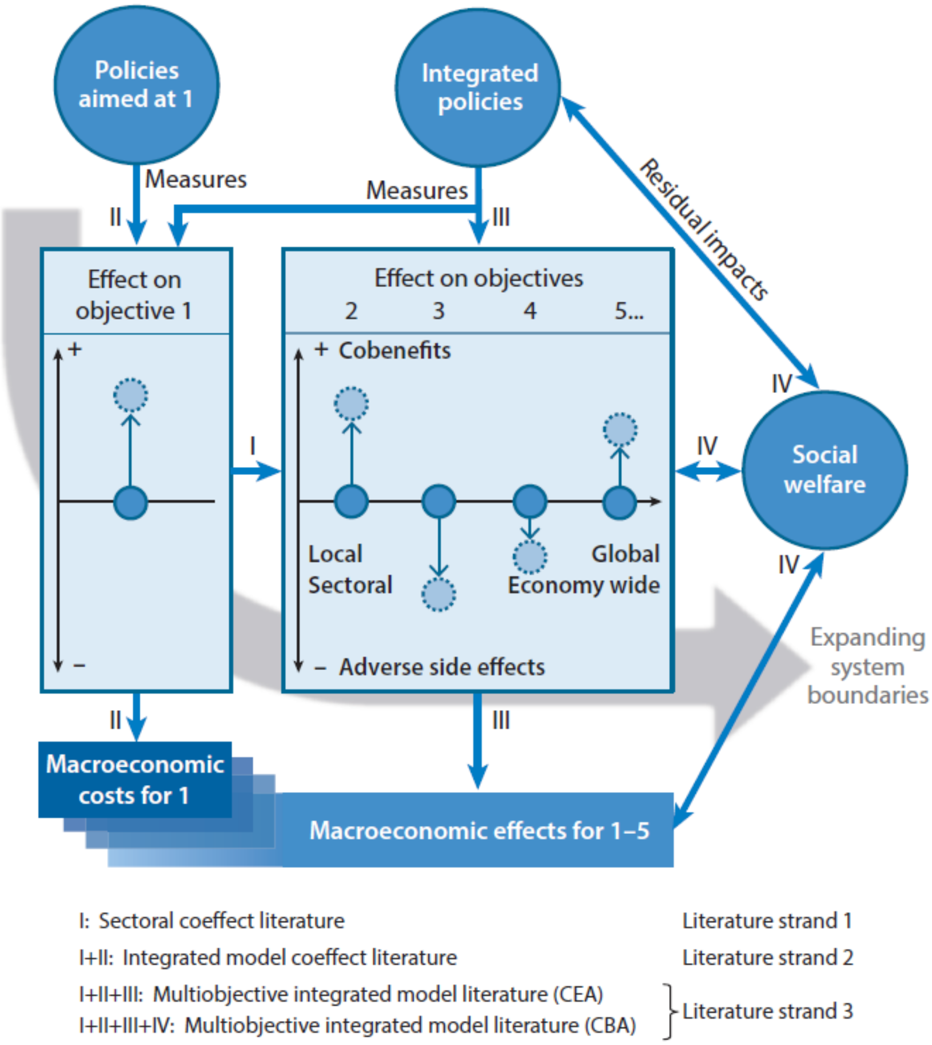

Figure 5.1 Schematic overview of important terms and concepts linked to the different literature strands on the interactions of mitigation, other objectives, and social welfare, following Equation 1. Abbreviations: CBA, cost-benefit analysis; CEA, cost-effectiveness analysis.

Literature strand 2 (from climate policies to mitigation measures to multiple objectives, see II in Figure 5.1) analyzes the implications of a stylized global climate policy (i.e., a global mitigation goal) for other sustainability objectives via the deployment of globally cost-effective portfolios of mitigation measures and the resulting macroeconomic mitigation costs. The analysis has been largely limited to the co-effects of mitigation on one sustainability objective at a time—and in some cases vice versa (see Section 5.4.1). This body of research can be an important source of evidence for policy makers, potentially changing the incentive structure for global mitigation efforts if near-term benefits for other objectives (e.g., local air quality) are more explicitly taken into account (36, 38–44). This strand focuses, however, on the co-effects of mitigation pathways in non-monetary terms and neither explicitly considers interactions of climate and non-climate policies nor the resulting macroeconomic effects (beyond aggregate mitigation costs).[14]

Literature strand 3 (from integrated policies to measures to objectives to welfare; see III and IV in Figure 5.1) adds another step by not only considering how integrated policies (i.e., climate and non-climate) through different measures contribute to multiple objectives but also analyzes the policies' respective macroeconomic effects. To analyze the aggregated importance of the synergies and trade-offs between multiple objectives resulting from alternative policy packages on a global scale, different integrated models have sought to extend their system boundaries to embrace a multi-objective perspective. Because welfare effects are only significant in second-best environments (i.e., if there are multiple externalities that are not fully internalized; see Section 5.4.3), the existing studies look at a smaller set of objectives than the other literature strands to deal with rising complexity (see Section 5.4.2). Although one modeling approach compares many different future mitigation scenarios based on various combinations of policies to achieve different levels of multiple energy policy objectives [cost-effectiveness analysis (CEA), III in Figure 5.1], another modeling approach equalizes marginal costs (including residual impacts) and benefits (including avoided impacts) to determine socially optimal policy stringencies [cost-benefit analysis (CBA), IV in Figure 5.1]. Owing to major conceptual challenges in integrating several objectives in a decision framework, this evidence base is still in its infancy (7, 10, 34, 46, 47).

5.3 Sectoral research results on the co-effects of mitigation measures

This section provides a qualitative meta-analysis of the many existing studies on mitigation co-effects from the sector-specific research assessed in the WGIII AR5. Our goal is to expand its high-level findings and the associated implications for multi-objective decision making. The section also identifies the most important caveats that are associated with the quantification and global aggregation of co-effects—often

[14] Barker et al. (45) reviews studies that apply computable general equilibrium models for evaluating the welfare impacts of climate vis-`a-vis non-climate policies, but with a focus on specific regions and policies in the short to medium term (e.g., Chile and China). They are thus not suitable for drawing lessons for a global scale and longer time horizons.

referring to literature on air pollution because it is the most thoroughly researched co-effect (12, 36, 41).

The qualitative meta-analysis in Figure 5.2 on the potential co-effects of sectoral mitigation measures for a wide range of sustainability objectives builds on several hundred studies that were published after the WGIII AR4 (48) and assessed in the different sector chapters of the WGIII AR5 (20). Although the underlying studies were often conducted for locally specific circumstances, the potential for such effects in one location often implies that they are possible or even likely in other locations with similar circumstances. Some studies are able to draw on existing data for some of the sectoral measures (particularly bioenergy), but many studies on co-effects are forward-looking because many mitigation measures are not yet implemented for various reasons.

Owing to space constraints, Figure 5.2 focuses on the effects for which a considerable number of studies exist. To facilitate a structured overview, the mitigation measures on the demand side and the associated co-effects are classified into three broad strategies: (a) fuel switching to low-carbon energy carriers/fuels, (b) technical energy-efficiency improvements, and (c) energy demand reduction through other means (e.g., behavioural/structural changes)—largely following Edenhofer et al. (11, Table TS.3). The co-effects for the different sustainability objectives are classified along the three SD pillars—economic, social, and environmental [see Fleurbaey et al. (7) on the relation between multiple objectives and SD]. Although some objectives can be regarded as ultimate end points (e.g., health), others are intermediate end points (e.g., water pollution), following the availability of literature on the respective co-effects.

The extent to which any of these effects will eventually materialize also depends on other factors. These include the scale, scope, and pace of implementation of the mitigation measures, which are not discussed in detail here. In the Supplemental Material, the reader can find condensed information on the co-effects from Supplemental Table S-5.1 (available at http://www.annualreviews.org/doi/suppl/10.1146/annurev-environ-021113-095626 and in section 5.10) in the context of the appropriate sector. Two broad messages that are globally relevant for decision making can be derived from this meta-analysis:

1. For mitigation measures on the demand side, the potential co-benefits outweigh the risks; on the supply-side, the balance depends to a larger degree on the specific measure (1). This implies that efficiency and other measures to reduce sectoral energy demand are robust strategies across multiple objectives but that the overall co-effects of fuel switching are not as clear-cut (see further below in this section). In these cases, the number of potential positive versus negative effects is not necessarily a good indication for the net effect on welfare because some large effects in terms of the change of non-monetary indicators may have very small welfare effects—and vice versa (see Section 5.4.3).
2. Multi-objective decision making on climate change mitigation can build on a wealth of evidence of the different co-effects on many policy-relevant objectives. In fact, the scientific literature covers the co-effects of most sectoral mitigation measures

for energy security and reduced health and ecosystem impacts. This is, however, not the case for all objectives: Some effects seem to be rather idiosyncratic to specific (groups of) measures, as shown in the last column of Figure 5.2, highlighting the question of how to compare these different effects. If no arrow is shown, this can imply either that an effect is unlikely to materialize or that no scientific literature is (as yet) available.

	Sectoral mitigation measures		Economic			Social			Environmental			Other objectives
			Energy security	Sectoral productivity	Local/sectoral employment	Reduced health impact	Thermal comfort, work conditions	Safety/ disaster resilience	Reduced ecosystem impact	Reduced water use/pollution	Reduced land use	
Low-carbon energy supply	Nuclear	Replacing coal	↑[a]		↑	↑↓		↓	↑↓			Nuclear proliferation, nuclear waste
	Renewable (excluding bioenergy)	Replacing coal	↑		↑	↑			↑↓	↑↓		Energy access, particularly off-grid; Increased resource mining
	Coal with CCS	Replacing coal			↑↓	↓		↓	↓	↓		Long-term monitoring of CO_2
	BECCS (excluding coeffects of bioenergy)	Replacing coal				↓		↓	↓	↓		
	Bioenergy[b]		↑		↑↓	↑↓			↓[c]	↓	↓	Food security and equity in land tenure
Transport	Fuel switching		↑			↑[d]		↓	↑↓			Technological spillovers to developing countries
	Technical energy efficiency		↑			↑		↑	↑			
	Urban form/modal shift[e]		↑	↑	↑↓	↑		↑	↑		↑	Equitable mobility access
	Energy demand reduction via other means		↑	↑		↑			↑↓		↑	Reduced urban congestion
Buildings	Fuel switching		↑		↑	↑			↑			Reduced fuel poverty
	Technical energy efficiency[f]		↑	↑	↑	↑↓	↑	↑	↑	↑		
	Energy demand reduction via other means[g]		↑			↑			↑			
Industry	Fuel switching (including CCS)			↑		↑	↑		↑	↑		Increased competitiveness
	Technical energy efficiency		↑	↑	↑	↑	↑	↑	↑	↑		Technological spillovers
	Material efficiency				↑	↑		↑	↑			Reduced resource mining

Figure 5.2 The wealth of evidence from sectoral research on the potential co-effects of sectoral mitigation measures on additional sustainability objectives, described in part by the following colours and symbols: green arrows/text, potential co-benefits; orange arrows/text, potential adverse side effects; smaller arrows, small-scale effects by comparison; blank cell, the effect is either unlikely or is not reported in the literature; grey-shaded cells, potential effects also possible outside the location of implementation. Figure 5.2 is based on a qualitative meta-analysis of the sectoral literature on non-monetary indicators for co-effects in the WGIII AR5 sector chapters on energy supply (21), the transport sector (54), the buildings sector (52), the industry sector (147), and bioenergy (102). Abbreviations: BECCS, bioenergy and CCS, i.e. the application of CCS technology to bioenergy conversion processes; CCS, carbon dioxide capture and storage.

[a] Relates to reduced exposure to fuel price volatility; the concentration of the nuclear supply chain may, however, lead to long-term stresses (148).

[b] The co-effects of bioenergy heavily depend on the development context and the scale of the intervention. Other agriculture, forestry and other land-use (AFOLU) measures are not included in this figure because they are not directly related to energy transition (see 26, 102, and 109 for an overview).

[c] This is mainly valid for large-scale monocultures.

[d] Excluding diesel.

[e] Land-use planning can create the underlying conditions for collocated higher employment and residential densities that are necessary to support the use of public transport (see 18).

[f] Including efficient equipment as well as insulation interventions.

[g] Based mainly on behavioural changes.

It is, however, difficult to gain more than qualitative insights for policy making in one location if the quantitative evidence is based on locally specific circumstances, policies, and assumptions from another location. For example, the net effect of fuel switching on other objectives depends on the extent to which the benefits of switching away from high-carbon energy carriers dominate the context-specific balance of co-effects arising from the increased supply of low-carbon energy carriers. The net effect also depends on how individual measures are implemented, affecting the degree to which each unit of low-carbon energy actually replaces one unit of high-carbon energy (49). Many studies discuss the example of biofuel deployment and its effect on total global fuel consumption, but they do not agree on its quantitative importance (e.g., 50, 51). In the same way, energy-efficiency measures in the energy demand sectors may not necessarily lead to the possible energy demand reductions because rebound effects can occur. These also differ across different locations (52, 53). In fact, a multitude of changes (e.g., in climate and non-climate policies, energy prices, and energy supply and demand resulting from technological and behavioural changes) makes any comprehensive analysis highly complex, and estimations of these rebound effects vary widely (21, 54, 55). Figure 5.2 addresses this challenge of context-specific circumstances by assuming, in the first part of the figure, that each unit of low-carbon energy supply replaces one unit of coal (instead of a locally specific energy mix). This specification is required to establish a baseline against which the lower-carbon energy supply technologies can be evaluated with respect to other objectives.

This implies that any quantifiable results reported in the literature depend largely on the system boundaries chosen for the analysis of individual studies. In contrast to the cross regional, cross sectoral mitigation perspective adopted by the integrated models discussed in Sections 5.4 and 5.5, sectoral research on co-effects often focuses on a particular location/country. This allows the research to take into account locally specific detail, which in turn is useful for informing local/national policy priorities and processes, but this level of detail is less useful as a basis for generalized results. The diverging foci can partly be explained by the fact that mitigation effects are independent of the location of GHG emission reductions, whereas many of the co-effects are most salient as policy drivers at the local scale (19, 41, 56).[15]

Moving beyond technological aspects, the empirical projections for co-effects of individual sectoral studies also depend on explicit or implicit assumptions on the effectiveness of existing or planned non-climate policies at the national and local levels that target the non-climate objectives directly, i.e., the projected baseline developments in the absence of climate policies (35, 43, 55, 60, 61). For example, the effects of mitigation measures on air pollution usually differ between wealthier and poorer countries; there are more stringent air quality policies in richer places and, hence, a lower base of pollutants squeezing the potential health gains (35, 41, 57, 59, 62, 63). The extent to which co-effects materialize also depends on geographical characteristics—

[15] The most notable exceptions are emissions of non-GHG air pollutants, which are reduced along with GHG emissions reductions when fossil-fuel combustion is avoided. The analysis of many air pollutants also draws on regional and global models (see, e.g., 43, 57–59) because the impacts are not confined to the location of emission. See section 5.4.1 for a discussion of their climate effects.

even within an individual country where differences can arise, for example, between rural and urban environments. Socioeconomic circumstances that cannot be shaped by policies, at least in the near to medium term, such as different indoor/outdoor activity patterns and the concentration of population, can also impact the associated exposure to air pollution (29, 35, 45, 64).

Despite these caveats in quantifying the co-effects of mitigation policies in non-monetary terms, many researchers have gone one step further by monetizing them. They build on economic valuation techniques that are used in research fields such as health and environmental economics (12, 34, 64). Some of the studies on monetized health co-benefits through air quality improvements, for example, cover a wide range of estimates: $2–840 per ton of CO_2 saved (see 41 for an overview, 59 for the upper estimates). This is due to, inter alia, consideration of diverse locations, mitigation and air quality policies, pollutants, impact channels, economic sectors, time horizons, and valuation techniques (see, e.g., 35, 41, 45, 55, 65).

In conclusion, many of the qualitative results for the various co-effects of mitigation measures derived for a single location are critical for decision making in that location. They can also be helpful for decision makers elsewhere to gain an overview of the potential effects of the many available sectoral mitigation measures. At the same time, any quantitative aggregation of sectoral research results on co-effects, particularly at a global scale, beyond the qualitative meta-analysis presented above, remains challenging owing to the incommensurability in results across effects, sectors, and locations—despite the vast amount of literature that has recently developed. Such an aggregation is, however, a prerequisite for a detailed understanding of the importance of global-scale synergies and trade-offs across mitigation and the many other global-scale sustainability objectives. The next section discusses quantitative results from integrated models on these interactions, building on a unified framework of analysis with respect to future global climate policy and a number of harmonized exogenous key parameters across models (see Supplemental Material Section 5.10.1). This makes their results at the global level more comparable and accessible to decision makers, but it is at the expense of the rich sectoral details presented above.

5.4 Integrated model results on the interactions of multiple sustainability objectives

The results of the interactions of mitigation and other sustainability objectives from integrated model studies assessed in the WGIII AR5 (1) are further condensed and discussed in this section to expand on the high-level findings and the associated implications for multi-objective decision making. One important advantage of this literature is that the deployment projections capture cross regional and cross sectoral interactions of mitigation measures.[16] On the basis of methodological insights in analyzing the co-effects on specific objectives from the sectoral literature (see Section

[16] To keep model complexity manageable, however, this strand of literature typically projects the effects of stylized policies rather than considering detailed policy instruments. It ignores the potential interactions between different mitigation policy instruments on different governance levels (19, 66).

5.3), the integrated models have expanded their system boundaries to analyze the interactions of global mitigation goals and additional objectives in one research setup, such as air quality and its health implications, energy security, energy access, as well as minimizing energy-related biodiversity loss and water and land use. Although the majority of these studies focus on the co-effects of mitigation pathways on one other objective, or vice versa, in non-monetary terms (see Section 5.4.1), a few recent analyses have looked at the interactions of integrated policies for multiple objectives, in some cases even taking welfare effects into account (see Section 5.4.2). A thorough analysis of such welfare effects with numerical models requires a consistent formulation of policy and counterfactual baseline scenarios. Section 5.4.3 critically discusses these issues as well as the associated cost metrics used in integrated models to convey information on macroeconomic and welfare impacts.

5.4.1 Integrated model results on the co-effects of mitigation pathways

In the integrated model literature, there is growing attention paid to the interactions of mitigation and non-climate objectives (8, 67). Figure 5.3 offers a condensed overview of those studies looking at (a) the co-effects of different mitigation pathways and (b) the reverse direction, i.e., the effect on climate change if, for example, air quality policies are pursued (indicated by the arrows in the second column).

An increasing body of literature has explored the linkages between air pollutant and climate policies (see 68 and 69 for a review). These studies indicate significant co-benefits of mitigation for a number of different air pollutants—up to 50/35/30/22% reductions by 2030 of sulfur dioxide (SO_2), nitrogen oxides (NO_x), 2.5-µm particulate matter ($PM_{2.5}$), and mercury (Hg) emissions or concentrations against baseline scenarios, respectively (8, 43, 70, 71).[17] At present, only a limited number of global-scale integrated models are able to analyze these effects in some detail. The current versions of these models typically estimate the physical air pollution co-benefits of technological changes motivated by mitigation activities (63); in some cases, air quality and human health impacts are also calculated (43). However, explicit representations of air pollution control costs are for the most part not included. What some of the scenarios do consider are clearly specified policy packages for air pollution control, finding that the co-benefits of mitigation depend on the stringency of current and planned air pollution legislation (cf. Sections 5.3 and 5.4.2) (e.g., 40, 69). Other studies have meanwhile analyzed the reverse mechanism: the impacts of air pollution control measures on the global climate. A key point here is that many of the air pollutants also impact radiative forcing as they form aerosols or act as precursors of aerosols or GHGs. There is, however, great uncertainty in the estimates (38, 63, 72–75). Studies focusing on the co-benefits of air pollution policies for mitigation show that they can potentially reduce net radiative forcing and midterm temperature change by up to 0.2°C by 2030. This can only occur, however, under somewhat debatable assumptions, such as limited or no improvements in the control of air pollutants that cool Earth (e.g., SO_2, NO_x) (58, 69, 75).

[17] Because the deployment projections are uncertain with respect to the role of individual measures (even for a particular mitigation goal, such as the 2°C target) and different models show different results (see Supplemental Material Section 5.10.1), the ranges for these results are relatively large (see Supplemental Figure S-5.2 for BC and SO_2 emissions).

Direction of analysis between objectives			Indicators used most prominently	Direction of coeffects	Scale of coeffects	Key determinants for the scale of the coeffects	References
Climate change mitigation	→	Air quality and health	SO_2, NO_x, $PM_{2.5}$, Hg emissions or concentrations	↓	2030: up to 50/35/30/22% reductions	Stringency of current/ planned air pollution legislation, ratio of abated warming versus cooling air pollutants	8, 38, 43, 58, 63, 69–72, 75, 120
	←		Midterm global temperature change	↓↑	2030: fraction of 1°C in both directions (effect low after 2050)		
	→	Energy security	Fuel diversity of electricity	↑	2050: 13–36% increase	Energy resource endowment, type of policies pursued, energy supply restrictions and current and future usage	8, 78, 80, 81, 83, 85, 87, 95
	→		Import dependence	↑↓	2050: 10–70% decrease[a]		
	→		Cumulative oil extraction	↓	2050: 2–36% decrease		
	←		GHG emissions	↑	Higher CO_2 emissions versus baseline		
	→	Energy access[b]	People with modern energy access, GJ per capita	↑↓	Unclear net effect (off-grid RE access versus higher energy prices)	Type of fuel used by the poor and policies to support switch to modern energy services	8, 43, 67, 96–98, 100
	←		GHG and SLCP emissions	↑↓	Unclear net effect (more GHGs/less SLCPs)		
	→	Biodiversity loss	Loss in MSA	↓↑	2050: 50% decrease of MSA loss possible (direct and coeffect)	Land-use policies and policies for re/afforestation and bioenergy	67
	←		CO_2 emissions from land use	↓	2050: lower CO_2 emissions	Ecosystems protection policies	
	→	Land-use impact	Million hectares in global land-use change	↑	Higher land-use change versus baseline (high variance across models)	Land-use policies, policies for re/afforestation and bioenergy, soil quality, yield growth	103–105, 110, 121, 149–152
	→	Water-use impact	Number of people in severely water-stressed regions	↓↑	2050: -8–3% (most studies: small reduction) (direct and coeffect)	Implementation practice of water-intensive mitigation options (e.g., bioenergy, afforestation)	67, 114, 115, 122, 153

Figure 5.3 Overview of integrated model literature results on interactions of mitigation and other sustainability objectives on a global scale as reviewed in Clarke et al. (1, sections 6.3.5 and 6.6), described in part by the following colours and symbols: green arrows, potential co-benefits; orange arrows, potential adverse side effects; smaller arrows, small-scale effects by comparison; grey-shaded cells, research that analyzed the co-effects of pursuing sustainability objectives on mitigation goals. Studies that looked at integrated policies for achieving multiple objectives are discussed in Section 5.4.2, but their results are also included in this figure. Abbreviations: CO_2, carbon dioxide; GHG, greenhouse gas; GJ, gigajoule; Hg, mercury; MSA, mean species abundance; NO_x, oxides of nitrogen; $PM_{2.5}$, particulate matter 2.5 micrometers in diameter or smaller; SLCP, short-lived climate pollutant; SO_2, sulfur dioxide.

[a] Interregional energy trade is used in the underlying studies as a global proxy for regional import dependence.

[b] Energy access here refers to basic needs for clean, reliable, and affordable energy services and should not be confused with the increased demand for energy services that, at least historically, has been driven by broader economic growth (1).

Current science indicates that such climate benefits decrease with increasing mitigation efforts and, more generally, depend greatly on which air pollutants are reduced and to what extent. This is because emissions of SO_2 and NO_x mask global warming because of their cooling effects, whereas emissions of black carbon (BC) and tropospheric ozone precursors contribute positively to radiative forcing (55, 72). Several studies go further by noting that reductions in short-lived climate pollutants do not buy substantial time for CO_2 emissions reductions but can complement concerted mitigation efforts (69, 76, 77). Air pollution policies that are not focused on the co-benefits for mitigation could even exacerbate global warming (63).

A growing body of literature focuses on the energy security implications of climate change mitigation scenarios. From the perspective of energy sovereignty (or risks arising from foreign actors), most of the literature finds that energy trade and imports decline as a result of mitigation (8, 78–82). The bulk of this co-effect emerges after 2030, however, because in the short-term mitigation limits domestic coal deployment, which counterbalances the increase in domestic renewables (83). In addition, the increased sovereignty of major importing countries is likely to result in a drop in energy export revenues for the Middle East, the former Soviet Union, and possibly the United States (84–89).[18] Moreover, geographic diversity of production has been found to increase as fossil fuels are phased out of the system (78, 88). The upside of lower extraction rates is less concern over resource scarcity and the related price volatility (78, 83, 93). The literature also finds that mitigation leads to greater resilience from diversification of energy sources in transport and electricity (8, 78, 80, 83). What the scenario literature on the linkages between energy security and mitigation does not include are, for instance, a broad treatment of the robustness concerns related to systemic failures from discontinuities and shocks (94) and a more systematic analysis of the climate implications of policies targeted at energy security than has been done previously (40, 95).

The impact of climate policy on energy access depends strongly on how the policy is actually implemented. Although the transition from traditional to modern energy could become somewhat more expensive if GHG emissions were priced universally (96), staged implementation of climate policies or dedicated policy schemes could lead to very different results (67). In least-developed countries with a high potential for off-grid technologies, scenario studies have shown that the deployment of renewable energy can help promote access to clean, reliable, and affordable energy services (97, 98). The impacts of policies promoting energy access on climate change are projected to be very small (67, 99). As energy consumption of the world's poorest is very low and modern energy carriers can be used much more efficiently than traditional ones, studies have shown that there is negligible impact on global CO_2 emissions over baseline levels, even if traditional biomass is completely replaced by fossil fuels (100, 101).[19] Moreover, the use of modern energy also reduces emissions of BC, further reducing the net impact on climate (38, 58, 72).

The interactions between climate policy and biodiversity are complex and beset with increased uncertainty from a lack of knowledge regarding the detailed functioning of complex ecosystems. The impact of climate policy on biodiversity particularly depends on the net impact of avoided climate change (and associated changes in air pollution) and the possible impacts of mitigation measures, such as the use of bioenergy and forestry-related measures (the impact here depends on the specific measure). Van Vuuren & Kok (67) show that unless bioenergy is regulated the negative impacts might, in future decades, dominate the positive ones. In the opposite direction, policies to preserve biodiversity could lead to a reduction of CO_2 emissions from land use if they lead to a larger forest area on a global scale (67). This not only depends on local policies to protect specific ecosystems but also on land-use policies in different areas of the world in general (given the potential impacts on food trade).

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[18] Though a few studies argue that if costs of unconventional oil were high enough conventional oil producers may actually benefit from climate policies because this market structure would increase the marginal price of oil (90–92).

[19] Pachauri et al. (100) argue that achieving universal energy access could even reduce global GHG emissions, assuming that 20% of traditional biomass is unsustainably harvested today and hence adds to current net GHG emissions.

The relationships between land use and climate policy are complex as several very uncertain relationships exist, and different policies can have very different impacts. For instance, mitigation scenarios tend to use large levels of bioenergy. Models show that this can significantly influence land use or land tenure as land is needed for bioenergy production, potentially leading to a reduction of natural areas (and associated GHG sinks and/or areas for food production). The exact impact depends on assumptions and modeled impacts on (induced) yield changes, dietary patterns, trade policies, land policy, and other GHG policies. The latter could, for instance, lead to an incentive not to increase (or even decrease) the natural area. At the moment, most integrated models only capture some of these relationships, and the net impact is difficult to assess given the uncertainties involved (24, 27, 29, 67, 102–105).[20] Most studies agree that overall it is important to account for the adverse side effects of large-scale use of afforestation and bioenergy, particularly because of food security and land tenure concerns (see 26, 103, 109–111 for a more in-depth discussion and assessment of many other SD implications).[21] This is why many scenarios in the literature explicitly consider futures with limited supplies of biomass for bioenergy purposes; although this may lead to higher mitigation costs in total, the SD risks could be lower (113).

A few studies have looked at the relationship between climate policy and water use. Mitigation reduces water use for fossil-fuel power plants (114; also see Supplemental Material Section 5.10.4 on energy supply for the varying effect of deploying different renewable energy technologies) but could increase water use for bioenergy production (115, 116; also see Supplemental Material Section 5.10.4 on bioenergy). In addition, mitigation influences the precipitation and evaporation changes associated with climate change, but these are very uncertain (117). Given these uncertainties, it is challenging to conclude anything on these net impacts at the moment.

Taken together, the overall evidence on the implications of stringent mitigation goals on other objectives—particularly from multimodel scenario results—is very relevant for multi-objective decision making. For instance, the integrated model literature confirms the insights from more sectoral studies (condensed in a qualitative way in Figure 5.2) that the co-effects of mitigation goals on air quality and energy security via the many sectoral mitigation measures are positive and shows that they are often projected as substantial. At the same time, this synergy is less clear or entirely reversed for the mitigation benefits of policies primarily targeted at air quality or energy security.

The majority of the model studies, however, have only explored the co-effects of mitigation on a single additional objective—or vice versa. The next section discusses the recent body of strand 3 literature, which takes a more comprehensive and holistic

[20] Under the heading of water-land-energy nexus, however, local trade-offs are analyzed by a growing research community (e.g., 106–108).

[21] One recent model intercomparison (the first for agro-economic models) found that the effect of lignocellulosic bioenergy deployment, rising to about 100 EJ by 2050, on food prices is significantly lower (5% higher prices on average across models) than the potential effects induced by climate impacts on crop yields in a high-emission scenario (25% higher prices on average across models) (112). Because these effects are closely related to land-use impacts, they are not separately shown in Figure 5.3.

perspective to explore the interactions of multiple objectives in one study and how to reach them simultaneously with integrated policies.

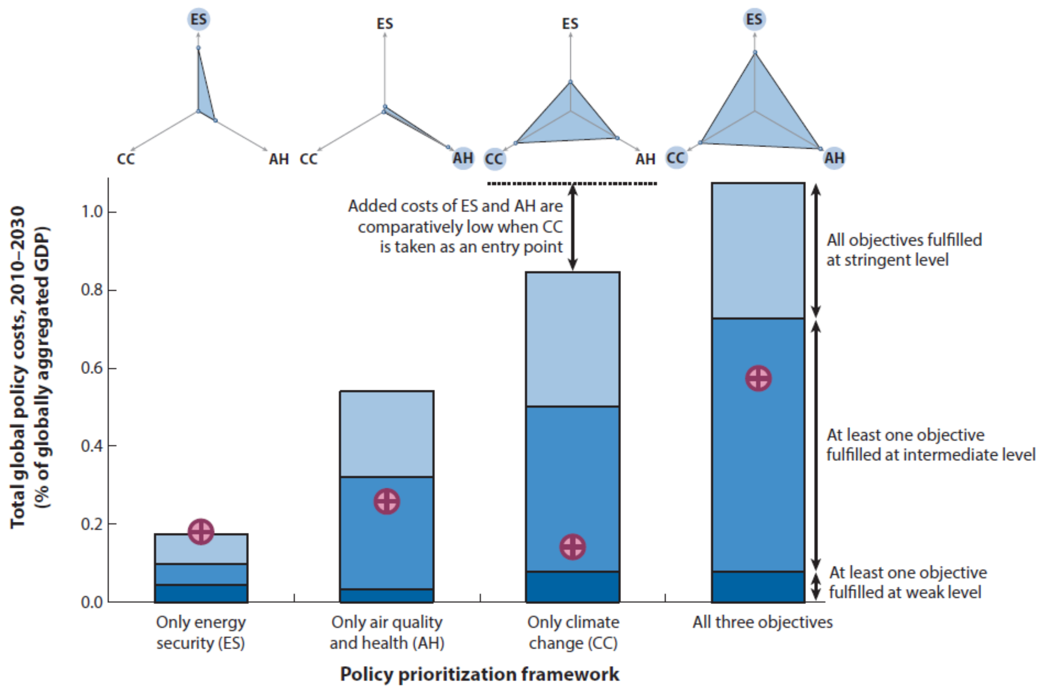
5.4.2 Integrated model results on integrated policies for multiple objectives

Some of the modeling teams further broadened the scope of their model tools to analyze integrated policies, which simultaneously achieve multiple objectives: Bollen et al. (95), scenarios developed in the context of the Global Energy Assessment (118; see 8, 40,119), Rao et al. (43), van Vuuren & Kok (67), Rogelj et al. (69), Chuwah et al. (120), Calvin et al. (121), and Akimoto et al. (122).[22] The former two studies quantify key interactions in economic terms on a global scale, which is why they are discussed in more detail in this section. As outlined by Edenhofer et al. (28) and in Section 5.4.3, analysis of integrated policies, the associated effects on multiple objectives, and the effects on macroeconomic costs or welfare metrics imply consideration of multiple externalities—either explicitly or implicitly.

Bollen et al. (95) developed a set of scenarios using a social welfare optimization approach to assess the costs and benefits (both market and external) of climate, air pollution, and energy security policies, either in isolation or in an integrated way (i.e., a CBA, see the pink circles in Figure 5.4). The GEA scenarios, as pictured in McCollum et al. (119), focus on the same subset of energy policy objectives but instead use a set of normative policy targets (implicitly assuming a second-best environment, i.e., that pre-existing externalities are not sufficiently internalized; see Section 5.4.3) and a large ensemble of scenarios to determine ranges of costs for policy packages of varying stringencies and forms (i.e., a CEA, see Figure 5.4 and the table below to explain the three stringency levels for each objective). For both sets of scenarios, Figure 5.4 shows global policy costs as a percentage of globally aggregated gross domestic product (GDP) between 2010 and 2030 of pursuing one of the three energy policy objectives in isolation (the three leftmost bars/circles) or all of them simultaneously with integrated policies (rightmost bar/circle). For a discussion of the different welfare metrics used by the two studies, please refer to Section 5.4.3.

Both studies find substantial synergies across the different objectives. McCollum et al. (119) show that global policy cost reductions can materialize—particularly in the near term—if multiple objectives are pursued with integrated policies rather than in isolation. Note, for example, that the sum of the costs represented by the three leftmost bars is much greater than the costs represented by the rightmost bar. These cost synergies arise, for example, through reduced financial requirements for end-of-pipe air pollution control equipment and imported fossil fuels in a decarbonized energy system (see Figure 5.3). Similar findings have been made for regional assessments of the economic implications of co-benefits (57, 128, 129), but the literature reviewed here is the first to evaluate these effects on a global scale.

[22] Although the literature on low-carbon society pathways considers multiple sustainability objectives in an integrated way, the models are calibrated to national scales only, which is why they are not discussed here (123–127).



Fulfillment	Energy security (ES) Global primary energy trade (EJ/year) 2030	Air quality and health (AH) % reduction in global health impacts from baseline 2030	Climate change mitigation (CC) CO_2-equivalent (CO_2eq) concentration ranges in 2100
Stringent	<120	>80%	<465 ppm CO_2eq
Intermediate	120–140	25%–80%	465–700 ppm CO_2eq
Weak	>140	<25%	>700 ppm CO_2eq

Figure 5.4 Costs of achieving three energy policy objectives for different policy prioritization frameworks. For McCollum et al. (119) (blue bars), policy costs are derived from an ensemble of >600 scenarios and represent the net financial requirements (cumulative discounted energy-system and pollution-control investments, variable costs, as well as operations and maintenance costs) over and above baseline energy-system development, which itself is estimated at 2.1% of the global gross domestic product (GDP). For Bollen et al. (95) (pink circles), policy costs are derived from a set of four distinct scenarios and are calculated as GDP losses (cumulative discounted) relative to a no-policy baseline. Triangular schematics summarize the performance of scenarios from McCollum et al. (119) that achieve stringent fulfilment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes). Sources: Riahi et al. (8), Bollen et al. (95) and McCollum et al. An integrated approach to energy sustainability. *Nat. Clim. Change*, 1(9): 428–9 (2011), used with permission of Springer Nature.

Other near-to-midterm synergistic effects of mitigation activities, also identified by Bollen et al. (95), include improved air quality (hence, lower health impacts) and enhanced energy security through fuel diversification by lowering the reliance on oil and gas demand and imports. As many of these synergies come about through energy and carbon intensity reductions, climate policy may be seen as a strategic entry point for reaping these benefits. It should be mentioned, however, that the co-benefits of stringent climate policies for energy security, air quality, and health, respectively, will be much less pronounced if future policies for air pollution and energy security are more aggressive than currently planned, as discussed in Section 3 (see 43, 69, and 120 for a detailed discussion of the implications of different air pollution control stringencies).

The integrated model studies presented in this section are the most comprehensive efforts to date in integrating many of the steps from the welfare-theoretical framework presented in Section 5.2 and showing conclusive quantitative results on a global scale.

At the same time, these studies show the limits of integrating all these aspects into a single analysis framework. This is because they have to reduce the scope of analysis at each step, unlike in other literature strands, thus highlighting the value of each individual strand:

1. To keep model complexity manageable, these two studies focus on a smaller set of (energy policy) objectives, compared to the objectives considered in the sectoral research (literature strand 1, condensed in Figure 5.2) and even compared to model results on co-effects (literature strand 2, condensed in Figure 5.3).
2. Because these studies are each based on single models, the entire uncertainty range of deployment projections (see Supplemental Material Section 5.10.1) and the associated co-effects (as evidenced by the wide ranges from literature strand 2 in Figure 5.3) cannot be fully considered.
3. The determination of optimal levels of multiple objectives is prone to assumptions and value choices and largely hypothetical for nonmarket goods, so this small set of studies that analyze macroeconomic implications across multiple objectives reduce the complexity of the task by resorting to a range of simplifying assumptions. McCollum et al. (40), for instance, avoid explicit analysis of externalities and determination of welfare optima by considering a set of three possible stringency levels of policy targets from the political arena; this circumvents the (locally) contested nature of the priority levels attached to many objectives. By contrast, Bollen et al. (95) choose a relationship between income and the value of statistical life as well as specific parameters for the penalty function for energy security deficiencies and for the climate change damage function; these all predetermine the priority setting across the analyzed objectives; yet, despite the sensitivity analysis conducted, the choice of these values/parameters/functions does not cover the wide range of estimates available in the relevant literature.

The analysis of additional objectives relevant for multi-objective decision making in the future would require consideration of the locally specific priority settings and policies, their non-climate and climate effects on a global scale, and their implications for macroeconomic costs and welfare. Because such research is not yet available, Section 5.5 presents a complementary approach, which usefully juxtaposes sectoral research and integrated model results. Section 5.4.3 critically discusses the degree to which the integrated assessment of costs, benefits, and co-effects of mitigation can be embedded in a welfare framework, and how this depends on the modeling approach.

5.4.3 Critical discussion of policy costs and welfare effects in integrated models

In Section 5.2, co-benefits and adverse side effects were introduced as part of a welfare-theoretic framework. We now show how the analysis of co-effects in integrated models can be related to this framework. Such models are dynamic numerical tools that explore the impact of transformational policies on the coupled energy-economy-environment system over a longer period of time (see Supplemental Material Section 5.10.1, for more details). By definition, such policies lead to nonmarginal changes in economic activity and social welfare. The related economic costs and welfare effects of a policy are usually measured against a counterfactual baseline case, which is used as a point of reference for the analysis. Integrated models come in various types (see Supplemental Table S-5.1 in the Supplemental Material Section 5.10.3) and thus have different capabilities of measuring the economic costs and welfare effects of policy changes. Two dimensions are relevant here: (a) the coverage of policy impact channels in terms of their economic costs and their benefits for societal objectives and (b) the degree to which (changes in) welfare can be measured.

Concerning coverage of policy impact channels, most models provide estimates of the direct economic costs of climate policies measured, for example, in terms of reduction in household consumption or economic output (2; see discussion below). A small, but increasing, number of models are also capable of capturing the direct costs of additional policies aimed at other non-climate objectives (see 40 and Section 5.4.2). Only a subset of models directly includes the economic benefits of policy intervention in terms of reduced climate damages (130–132; see 10 for a discussion). A full welfare analysis of costs, benefits, and co-effects of climate policy would require capturing the benefits and adverse effects of the whole policy portfolio on all relevant objectives and, in turn, the modeling of all impact channels through which the set of policies may alter the objectives (see 95 and Section 5.4.2). Such a complete CBA (e.g., following Equation 1) involves a series of heavily contested value judgments, is associated with a whole array of (additional) uncertainties in the valuation process, and hence remains a huge analytical and empirical challenge (cf. 10, 47). Those models that capture only policy costs are used for CEA, estimating the costs of reaching a set of predefined objective levels, for example, long-term climate targets (II in Figure 5.1) or targets for other objectives (III in Figure 5.1). Those models that additionally capture the policy benefits and residual impacts can also be used in a CBA mode to identify social welfare maximizing policies (IV in Figure 5.1).

Supplemental Figure S-5.3, in Supplemental Material Section 5.10.2, shows how this welfare effect can be decomposed into policy cost and benefit components and how the range of cost and welfare estimates emerging in CEA and CBA applications, as well as climate damage estimates, relate to each other. For example, the policy costs in a multi-objective setting in the case of McCollum et al. (40) are estimated by a CEA, considering the policy benefits in physical terms only (e.g., health benefits), rather than in economic terms. By contrast, Bollen et al. (95) include the disutility of air pollution, climate change, and energy insecurity in their study. A thorough understanding of how cost and benefit estimates relate to a social welfare approach is essential for a meaningful comparison of costs and benefits to assess overall welfare changes. Nevertheless, information about the individual components of welfare changes shown in Supplemental Figure S-5.3 is also particularly useful to evaluate policy trade-offs. Such information can be deduced from an analysis of subsystems, includes a smaller set of uncertainties and assumptions, and is based on models with better system representation. For example, policy cost estimates based on CEA do not need to make assumptions about climate damages that are still highly uncertain, particularly on a global level (see 22 for a discussion).

A second source of difference between cost estimates of different integrated models is related to the degree to which welfare can be measured. Partial equilibrium models can only explore economic impacts on the sectors that are represented in the model. They usually express policy costs in terms of changes to consumer and producer surplus. Estimates of welfare changes require a general equilibrium framework that can capture the macroeconomic impacts of policies and changes to other objectives (see Supplemental Table S-5.1 in the Supplemental Material Section 5.10.3). Monetary measures of welfare change in general equilibrium frameworks include equivalent variation and compensating variation, which describe how income would need to change to keep households just as well off after the implementation of a policy as before. As these are quite difficult to calculate and communicate, proxy measures for welfare changes, such as changes in household consumption, are used more frequently in integrated models (1). Changes in GDP are also commonly used, although GDP is a less satisfactory measure of welfare changes because it only captures economic output, rather than the welfare benefit it generates (47).

The introduction of a baseline scenario against which the welfare impact of a policy is measured gives rise to the notion of idealized (first-best) and nonidealized (second-best) policy environments (cf. 133). An idealized policy environment is one in which a single policy problem relating to a single objective exists; all other objectives are already achieved at their optimal levels in the baseline scenario (economically speaking, all externalities are already fully internalized). Economic theory stipulates that an idealized (first-best) policy consisting of ubiquitous Pigouvian pricing of environmentally damaging activities is optimal. In the case of mitigation, the idealized policy corresponds to comprehensive uniform GHG pricing in all sectors and regions, rising over time at a rate that reflects the cost increase of the next available unit of GHG emissions reduction. This is a useful analytical benchmark, included in most integrated modeling studies. However, co-effects do not have any value for society in such an idealized setting because the value of co-effects depends on the degree of internalization of existing externalities (34). These therefore need to be studied in nonidealized environments characterized by deviation from the optimal levels in more than one objective. In such circumstances, first-best policies may no longer be optimal (cf. 134). In some cases, climate policy could even lead to welfare losses if an already internalized externality was over corrected (34) or interacted with pre-existing inefficiencies in a welfare-degrading way (135, 136; also cf. literature on the double dividend, e.g., 137, 138). For example, if a climate policy can adversely affect other objectives, overall mitigation costs can rise. If co-benefits are dominant, by contrast, mitigation costs can be lower or possibly negative, even before factoring in the direct benefits of reducing climate change (see Figure 5.5). How large the value of co-effects would be is an empirical question; a major research challenge for the next generation of climate policy assessments.

An even bigger challenge is to integrate the perspective across mitigation and adaptation. Integrated models were originally developed and are still used to prescribe optimal policy, including impacts and adaptation in addition to mitigation. However, the vast majority of scenarios reviewed by the IPCC was based on CEA rather than CBA and had a narrow focus on mitigation. This was mostly owing to the uncertainty in estimating impacts and adaptation, and their dependence on the geographical scale (see Supplemental Material Section 5.10.1). Mitigation, adaptation, and damages are, however, highly interconnected, and joint assessments are receiving renewed interest (139). Few integrated studies have quantified the competition between mitigation and adaptation in terms of the allocation of investments (140, 141). Others have looked into the implications of including adaptation strategies on equity in international climate policy (142, 143). In all cases, mitigation and adaptation strategies are found to be complementary but with potentially important repercussions on mitigation costs and strategies, especially in terms of regional differences.

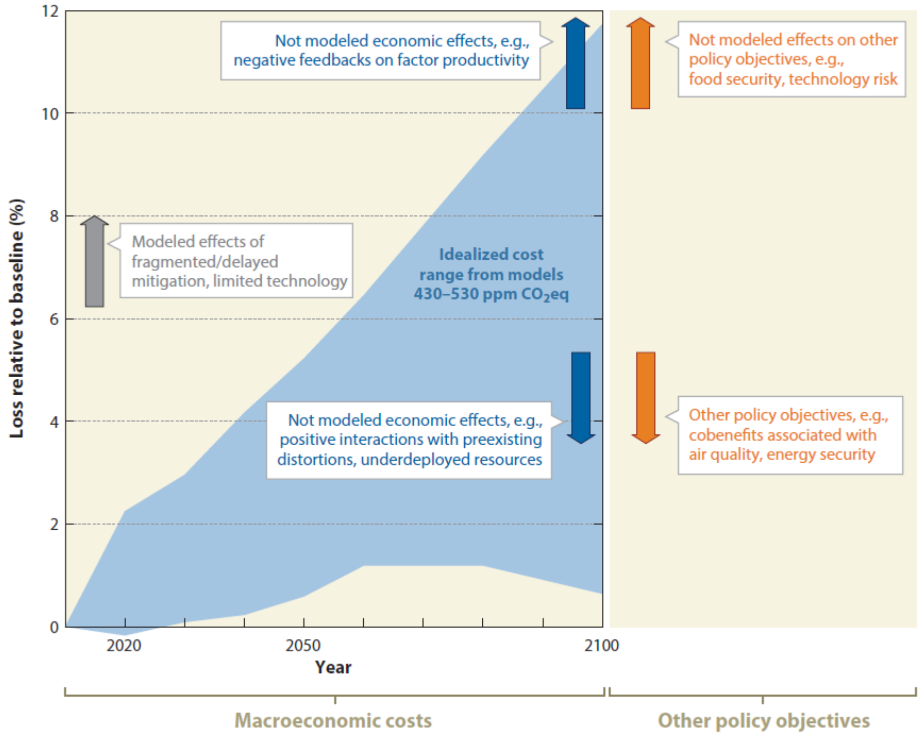


Figure 5.5. Stylized representation of mitigation cost impacts owing to considerations usually outside of those included in integrated models, such as co-effects. The plotted cost range refers to the percentage loss relative to baseline scenarios across models for cost-effective mitigation scenarios reaching CO_2-equivalent concentrations of 430–530 ppm (parts per million) in the year 2100 (25th–75th percentiles). Adapted from Krey et al. (133).

5.5 Untapped potential for further synthesis of existing research

The review and condensation of literature on the co-effects of mitigation measures and pathways in Sections 5.3 and 5.4, respectively, show that interesting and important insights can be gained from the different strands of literature. Across these strands, there is, however, a trade-off between the number of objectives analyzed in a study and its ability to present aggregated quantitative results. This is mainly caused by the challenges of linking results from the integrated model literature on the one the hand to the sectoral literature on the other. Recent attempts to tackle this analytical separation from within the integrated model literature (Section 5.4.2) have improved the integrated understanding but are limited in scope because studies need to find the right balance in handling complexity, providing transparency, and dealing with computational limitations. This section suggests a complementary synthesis, juxtaposing (a) quantitative evidence from a wider set of mitigation scenarios from integrated models consistent with the 2°C target and (b) qualitative evidence on the potential co-effects of mitigation measures on a wider set of sustainability objectives from sectoral research. Although such a synthesis also faces limitations, it is able to draw on the respective strengths of the somewhat disparate literature strands: (a) the ability of the different integrated models to take into account cross regional and cross sectoral interactions of mitigation measures and (b) the ability of the sectoral studies, taken together, to take into account the co-effects on a wider set of sustainability objectives and at a more disaggregate, detailed level.

In this context, Figure 5.6 presents the different sets of results in such a way that they speak to each other and so increase the understanding of relevant co-effects owing to global mitigation pathway choices. The figure draws on data for energy supply and demand projections (in primary and final energy terms, respectively) that are presented by a large group of integrated models for different sets of scenarios (from the WGIII AR5 Scenario Database, https://secure.iiasa.ac.at/webapps/ene/AR5DB). Ranges of scenario results are shown for those indicators that can be linked directly to the (groups of) mitigation measures for which co-effects are presented. Integrated models usually include all relevant energy supply technologies; however, the number of sectoral mitigation measures far exceeds the current limitations of complexity of the models. For each demand sector, the figure therefore focuses on the range of projections for total sectoral energy demand. It also centres on those high-carbon energy carriers that are most widely used today and whose reduction is linked most directly to the co-benefits presented on the right side. Finally, it shows the median projections of sectoral demand for electricity and bioenergy, which are the most important low-carbon energy carriers (see Supplemental Material Section 5.10.4). To show the effect of climate policies on the energy supply and demand projections, the figure shows baseline versus mitigation scenarios consistent with the 2°C target (as an illustration). This is for both standard (black ranges) and for low energy-intensity (EI) assumptions (blue ranges) in which the rate of EI reduction is consistent with and greater than historical developments, respectively. The figure thus allows the co-effects of the sectoral mitigation measures to be linked to the projected changes in crucial energy indicators. Even though the ranges are often wide, the changes in the median projections consistently show the following:

1. Increased attempts to achieve EI reductions in baseline scenarios (i.e., without targeted climate policies) lead to reduced demands and supplies of energy carriers in all sectors against the baseline; this implies that there would be a substantial number of potential co-benefits, particularly owing to reduced impacts of those energy carriers that are associated with the largest adverse side effects (oil, traditional biomass, and coal; see Supplemental Material Section 5.10.4). However, relying solely on optimistic EI reductions, without having a dedicated climate policy, does not allow the 2°C target to be achieved (1) as it only slows the growing oil and coal demand and may generate rebound problems (see Section 5.2).

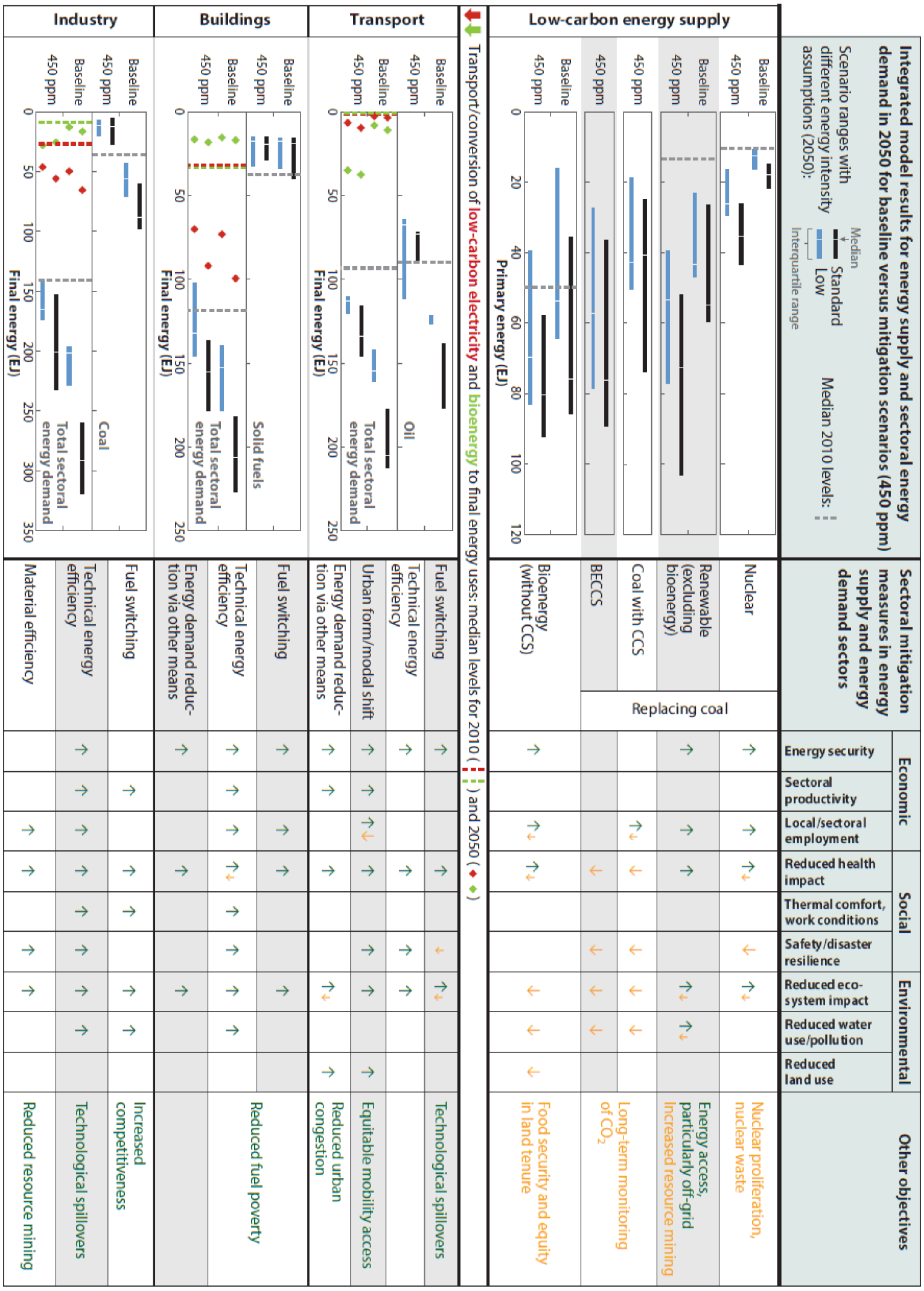


Figure 5.6 Scenario results from integrated models consistent with a 2°C target for different energy supply and demand indicators and the potential co-effects of (groups of) sectoral mitigation measures on additional sustainability objectives. Only scenarios with immediate mitigation and full availability of technologies are shown. Mitigation scenarios with CO_2-equivalent concentrations of 430–480 ppm (parts per million) in the year 2100 are indicated by 450 ppm. For details, see section 6.1.2 and Table 6.2 in Clarke et al. (1). Dark green arrows/text, potential co-benefits; orange arrows/text, potential adverse side effects; smaller arrows, smaller effects by comparison (see Figure 5.2 for details and notes). Abbreviations: BECCS, bioenergy and CCS; CCS, carbon dioxide capture and storage; CO_2, carbon dioxide; EJ, exajoule.

2. Projections for mitigation scenarios with standard EI assumptions not only require demand reductions against baseline and today's levels of oil and coal use but also result in an increased demand for biofuels and electricity from low-carbon sources. The balance of the local co-effects primarily depends on how and where the additional bioenergy is produced and which low-carbon electricity supply technologies are deployed where to satisfy the additional electricity demand (Section 5.3 and Supplemental Material Section 5.10.4).
3. Increased attempts to achieve EI reductions in mitigation scenarios lead to the lowest demand for all fossil-based energy carriers as shown in Figure 5.6. The additional supply of low-carbon electricity and bioenergy is lower than that of mitigation scenarios with standard EI assumptions. Maximizing synergies and minimizing trade-offs with non-climate sustainability objectives hence require that climate (and non-climate) policies be chosen in such a way that certain adverse side effects of bioenergy production are either avoided or carefully managed (24–26, 29, 102, 109, 113, and bioenergy supply in the Supplemental Material Section 5.10.4) and that low-carbon, but risky, energy supply technologies (e.g., nuclear and carbon dioxide capture and storage) are deployed in situations where they generate the lowest adverse side effects (see 21, 118, and energy supply in the Supplemental Material Section 5.10.4).

This synthesis offers a useful opportunity to draw on different strings of evidence from the somewhat disparate strands of literature at one glance and potentially increases our understanding of the implications of mitigation policy choices. Yet, Figure 5.6 offers neither quantitative results on the net global co-effects nor their impact on overall social welfare. To mitigate this shortcoming and better adapt these findings to the specific circumstances, this exercise could be repeated for those disaggregated scales that are still supported by the integrated models (for up to about two dozen world regions). This would give decision makers the opportunity to interpret the results against the background of regional contexts and priority settings (see, e.g., 39), circumventing some of the challenges of welfare accounting discussed in Section 5.4.3.

5.6 Conclusion and outlook

Based on a welfare-theoretic framework, the review and condensation of the WGIII AR5 results in this article show that the different strands of literature on co-effects have focused on different aspects of the interactions of climate change mitigation and other sustainability objectives; each strand of literature considered independently has remained partial in its ability to generate insights. This article also reveals that quantification and aggregation of co-effects are challenging because of the incommensurability and uncertainties of results that are all the more pervasive (a) the more the perspective shifts from sectoral and local to economy wide and global, (b) the more objectives are taken into account in the analysis, and (c) the more the results are expressed in economic rather than non-monetary terms.

Despite the growing insights into the co-effects of mitigation measures and recent efforts to conduct more integrated research, there are still substantial trade-offs (a) between the number of objectives analyzed and the ability to present quantitative results, particularly for overall welfare implications; and (b) between capturing synergies and trade-offs across different levels to inform global coordination and providing context-specific information necessary for local/sectoral policy making.

Literature strand 1 is able to analyze the effect on many objectives at a high degree of sectoral detail, and its meta-analysis in Figure 5.2 points to the important role of energy-efficiency improvements and other measures to reduce energy demand. The associated results are, however, very challenging to aggregate, particularly in monetary terms and on a global level. One reason for this is that they do not take into account cross sectoral or cross regional interactions—a prerequisite for cost-effective mitigation. Although literature strand 2 develops a better understanding of cost-effective mitigation pathways with respect to their implications for global co-effects in quantitative terms, revealing the salience of energy security and air quality co-benefits, it only analyzes a limited number of objectives. Lastly, literature strand 3 offers important insights into the welfare implications of pursuing three energy policy objectives either simultaneously or in isolation and reveals that climate policy is a good entry point to realize synergies across these objectives. The number of objectives analyzed is even smaller than in the second strand as is the ability to reflect the full range of uncertainty across different models. Future work can build upon these efforts.

To relax this trade-off to some extent, we present a way forward that draws on the existing strings of scientific evidence and builds on the respective strengths of the different literature strands without integrating them into a common modeling framework. Section 5.5 brings together in one figure (a) quantitative evidence on the future energy supply and demand in different sectors from a wider set of mitigation scenarios consistent with the 2°C target and (b) qualitative evidence on co-effects of mitigation measures on a wider set of sustainability objectives from sectoral studies. Although this approach does not eradicate the pervasive incommensurability and uncertainties, it makes them more transparent and accessible to decision makers. This synthesis tool allows decision makers to gain a better overview of, and to extract high-level insights into, the complex interactions of multiple objectives, revealing the following:

1. Mitigation pathways consistent with the 2°C target lead to a whole range of potential co-benefits and lower risks by reducing the use of fossil fuels and traditional biomass against baseline developments (and often current use); higher demand for low-carbon energy carriers might increase supply-side risks in specific local circumstances.
2. Faster-than-historical EI reductions lead to potential co-benefits and reduced risks in all sectors, irrespective of the scale of targeted global mitigation efforts. Combining optimistic EI reductions with stringent mitigation efforts leads to higher co-benefits and lower risks compared to mitigation pathways with standard EI reductions by reducing the demand for fossil fuels and traditional biomass and increasing the flexibility of choice between alternative mitigation measures. This allows better management of mitigation risks on the supply side

associated with the upscaling of low-carbon energy technologies and bioenergy supply.

The good news is that most risks on the supply side, which increase with the stringency of the mitigation goals, occur at the local scale and can be managed locally or nationally (except, perhaps, nuclear proliferation risks and the global aspects of food insecurity). Decision makers at the local/national level can exploit the increasing level of knowledge and the flexibility implied by the large range of results from mitigation scenarios (see Supplemental Material Section 5.10.1) to choose climate policies and mitigation measures according to their priorities for sustainability objectives. On the basis of existing literature, however, it is not possible to analyze the co-effects of these (sub)national measures on multiple objectives and their global mitigation effects in an integrated way, and vice versa, at least not for more than a small number of energy objectives (see Section 5.4.2). Despite a better understanding of the potential co-effects of different sets of mitigation pathways for a broader set of objectives (presented in Section 5.5), scientific evidence thus far only offers limited guidance for decision makers who seek to understand under which conditions and at which level synergies across multiple objectives can actually be realized and trade-offs avoided. Future research could advance the understanding of these complex interactions in three possible ways.

First, given that the trend is toward increased subnational- and national-level climate legislation and policy and that international cooperation is also increasingly focused on leveraging and enhancing these national measures (19, 144), greater attention to consolidating and summarizing co-effects at the national scale would be particularly helpful (see, e.g., 145). Similarly, there has been a proliferation of subnational decision making on climate issues, and other sustainability objectives (e.g., urban air quality) are almost exclusively handled at this level (18, 19). To serve these needs, future research should develop a multidimensional typology of co-effects beyond the classification into sectors, local or global effects, and sustainability aspects presented in Figure 5.2. This could then be used to target the specific types of challenges associated with the realization of synergies and the avoidance of trade-offs to more specifically target co-effects that map to decision-making jurisdictions, such as cities, states/provinces, and countries. For example, the typology could differentiate more explicitly among the co-effects that accrue locally and are primarily driven by local decisions (e.g., mobility access), those that accrue locally but are primarily driven by decisions made within the broader region (e.g., local agricultural yield gains through methane mitigation elsewhere), and those that accrue globally but are primarily driven by decisions made locally (e.g., technological spillovers). Other dimensions could include distributional, geographical, or timing aspects (i.e., which societal groups or stakeholders are most affected, and where and when they are affected). This would be useful for research that could choose the most appropriate methods, models, and system boundaries as well as for the political process that could focus on the most salient aspects of the interactions of multiple objectives.

Second, such a typology could be useful for a broader modeling strategy that could draw on the strengths of different methods by combining global-scale integrated models (which take into account cross sectoral and cross regional interactions) with national and subnational models (which are more spatially disaggregated and may have greater technological and sociodemographic details and heterogeneity). Although it may be too much to expect the hard coupling of these different tools, careful analyses within the framework of internally consistent scenario studies could permit a better accounting of national/local circumstances and preferences (along with their aggregate global/regional consequences), such as the level of socioeconomic and technological development, distributional aspects, risk perceptions, and priority settings for non-climate objectives.

Third, from a risk-management perspective, it is particularly important to differentiate between risks that can be managed locally (e.g., landscape impacts) and risks that can build up globally (e.g., for food security and nuclear proliferation). Future research could draw on the recent advances of integrated modeling with respect to more elaborate real-world assumptions for mitigation pathways, taking into account delayed and fragmented global mitigation efforts as well as the limited availability of mitigation technologies. Understanding the synergies and risk trade-offs across multiple sustainability objectives for alternative mitigation pathways would be an important contribution to a better-informed decision-making process at global and national/local levels.

Because many authors have argued for a more integrated policy approach to advance mitigation and additional sustainability objectives (e.g., 7, 10, 28, 39, 41, 43, 44), partly dissolving the analytical separation between the different sets of scientific evidence as done in this article is highly relevant for climate and sustainability policy choices. Better knowledge about the potential synergies and trade-offs across multiple objectives improves the understanding of this ends-means interdependency and may, according to Edenhofer & Kowarsch (31), even encourage decision makers to adapt existing priority settings to release political gridlocks, e.g., in international climate policy (cf. 146).

5.6.1 Summary points

1. The literature documents a large potential for co-benefits of mitigation for non-climate objectives, such as human health and energy security, but little is known about aggregated results and their overall welfare effects, particularly on a global scale.
2. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives but do not offer a systematic analysis of mitigation risks.
3. The incommensurability and uncertainties around quantification of co-effects become increasingly pervasive the more the perspective shifts from sectoral and local to economy wide and global, the more objectives are analyzed, and the more the results are expressed in economic rather than non-monetary terms. This reveals a trade-off between the number of objectives analyzed in a study and its ability to present aggregated quantitative results.
4. Drawing on different strings of evidence highlights the role of energy-efficiency and other measures to reduce energy demand for realizing synergies across multiple sustainability objectives and hedging mitigation risks on the supply side.

5.6.2 Future issues

1. Future research should develop a multidimensional typology of co-effects beyond the classification into sectors and sustainability aspects to inform (a) the choice of methods, models, and system boundaries in the analysis of a particular effect; and (b) the political process that could then focus on the most salient interactions of multiple objectives.
2. Greater attention to consolidating and summarizing co-effects at the local/national scale would be particularly helpful to better map to decision-making jurisdictions and the respective circumstances, preferences, and priority settings.
3. Future modeling efforts should draw on the strengths of different methods by combining global-scale integrated models (which take into account cross sectoral and cross regional interactions) with national and subnational models (which are more spatially disaggregated and may have greater technological and sociodemographic detail and heterogeneity).
4. Understanding the synergies and risk trade-offs across multiple sustainability objectives for alternative mitigation pathways would be an important contribution to better informed decision-making processes at global and national/local levels, drawing on the recent advances of integrated modeling with respect to more elaborate real-world assumptions, such as delayed and fragmented global mitigation efforts as well as limited availability of mitigation technologies.

5.7 Disclosure statement

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5.9 Literature cited

1. Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, et al. 2014. Assessing transformation pathways. See Ref. 20, pp. 413–506
2. Kriegler E, Weyant J P, Blanford GJ, Krey V, Clarke L, et al. 2014. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change* 123(3–4):353–67
3. Luderer G, Pietzcker RC, Bertram C, Kriegler E, Meinshausen M, Edenhofer O. 2013. Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.* 8(3):034033
4. Peters GP, Andrew RM, Boden T, Canadell JG, Ciais P, et al. 2013. The challenge to keep global warming below 2°C. *Nat. Clim. Change* 3(1):4–6
5. Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, et al. 2015. Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* 90(Part A):8–23
6. Rogelj J, McCollum DL, O'Neill BC, Riahi K. 2013. 2020 emissions levels required to limit warming to below 2°C. *Nat. Clim. Change* 3(4):405–12
7. Fleurbaey M, Kartha S, Bolwig S, Chee YL, Chen Y, et al. 2014. Sustainable development and equity. See Ref. 20, pp. 283–350
8. Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, et al. 2012. Energy pathways for sustainable development. See Ref. 118, pp. 1203–306
9. van Vuuren D, Nakicenovic N, Riahi K, Brew-Hammond A, Kammen D, et al. 2012. An energy vision: the transformation towards sustainability—interconnected challenges and solutions. *Curr. Opin. Environ. Sustain.* 4(1):18–34
10. Edenhofer O, Kadner S, von Stechow C, Schwerhoff G, Luderer G. 2014. Linking climate change mitigation research to sustainable development. In *Handbook of Sustainable Development*, ed. G Atkinson, S Dietz, E Neumayer, M Agarwala, pp. 476–99. Cheltenham, UK: Edward Elgar. 2nd ed.
11. Edenhofer O, Pichs-Madruga R, Sokona Y, Kadner S, Minx JC, et al. 2014. Technical Summary. See Ref. 20, pp. 31–107
12. Ürge-Vorsatz D, Tirado Herrero S, Dubash NK, Lecocq F. 2014. Measuring the co-benefits of climate change mitigation. *Annu. Rev. Environ. Resour.* 39(1):549–82
13. Edenhofer O, Flachsland C, Jakob M, Lessmann K. 2013. *The atmosphere as a global commons—challenges for international cooperation and governance*. Discuss. Pap. 2013–58. Harvard Proj. Clim. Agreem. http://belfercenter.hks.harvard.edu/publication/23364/atmosphere_as_a_global_commonschallenges_for_international_cooperation_and_governance.html
14. Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D. 1999. Revisiting the commons: local lessons, global challenges. *Science* 284(5412):278–82
15. Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. 2009. International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ.* 31(Suppl. 2):S64–81
16. van Vuuren DP, Weyant J, de la Chesnaye F. 2006. Multi-gas scenarios to stabilize radiative forcing. *Energy Econ.* 28(1):102–20
17. Dubash NK, Hagemann M, Höhne N, Upadhyaya P. 2013. Developments in national climate change mitigation legislation and strategy. *Clim. Policy* 13(6):649–64
18. Seto KC, Dhakal S, Bigio A, Blanco H, Delgado GC, et al. 2014. Human settlements, infrastructure and spatial planning. See Ref. 20, pp. 923–1000
19. Somanathan E, Sterner T, Sugiyama T, Chimanikire D, Dubash NK, et al. 2014. National and subnational policies and institutions. See Ref. 20, pp. 1141–205

20. IPCC. 2014. *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, K Seyboth, A Adler, I Baum, S Brunner, P Eickemeier, B Kriemann, J Savolainen, S Schlömer, C von Stechow, T Zwickel, JC Minx. Cambridge, UK/New York: Cambridge Univ. Press
21. Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, de la Vega Navarro A, et al. 2014. Energy systems. See Ref. 20, pp. 511–97
22. Kunreuther H, Gupta S, Bosetti V, Cooke R, Dutt V, et al. 2014. Integrated risk and uncertainty assessment of climate change response policies. See Ref. 20, pp. 151–205
23. Grieneisen ML, Zhang M. 2011. The current status of climate change research. *Nat. Clim. Change* 1(2):72–73
24. Creutzig F, von Stechow C, Klein D, Hunsberger C, Bauer N, et al. 2012. Can bioenergy assessments deliver? *Econ. Energy Environ. Policy* 1(2):65–82
25. Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, et al. 2014. Bioenergy and climate change mitigation: an assessment. *Glob. Change Biol. Bioenergy* 7(5):916–944
26. Creutzig F, Corbera E, Bolwig S, Hunsberger C. 2013. Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environ. Res. Lett.* 8(3):035047
27. Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O. 2012. Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nat. Clim. Change* 2:320–27
28. Edenhofer O, Seyboth K, Creutzig F, Schlömer S. 2013. On the sustainability of renewable energy sources. *Annu. Rev. Environ. Resour.* 38(1):169–200
29. Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, et al. 2011. Renewable energy in the context of sustainable development. In *Special Report on Renewable Energy Sources and Climate Change Mitigation*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, K Seyboth, P Matschoss, et al., pp. 707–89. Cambridge, UK/New York: Cambridge Univ. Press
30. van Vuuren D, Hoogwijk M, Barker T, Riahi K, Boeters S, et al. 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy* 37(12):5125–39
31. Edenhofer O, Kowarsch M. 2015. Cartography of pathways: a new model for environmental policy assessments. *Environ. Sci. Technol.* 51:56–64
32. Joas F, Pahle M, Flachsland C. 2014. Die Ziele der Energiewende: Eine Kartierung der Prioritäten. *Ifo Schnelld.* 67(09):06–11
33. Davis D, Krupnick A, McGlynn G. 2000. Ancillary benefits and costs of greenhouse gas mitigation: an overview. In *Ancillary Benefits and Costs of Greenhouse Gas Mitigation*. *Proc. IPCC Co-Sponsored Workshop, Washington, DC*, Mar. 27–29, pp. 9–49. Paris: Organ. Econ. Co-op. Dev.
34. Kolstad C, Urama K, Broome J, Bruvoll A, Cariño Olvera M, et al. 2014. Social, economic and ethical concepts and methods. See Ref. 20, pp. 207–82
35. Bell ML, Davis DL, Cifuentes LA, Krupnick AJ, Morgenstern RD, Thurston GD. 2008. Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environ. Health* 7:41
36. Jack DW, Kinney PL. 2010. Health co-benefits of climate mitigation in urban areas. *Curr. Opin. Environ. Sustain.* 2(3):172–77
37. Allwood JM, Bosetti V, Dubash NK, Gómez-Echeverri L, von Stechow C. 2014. Glossary. See Ref. 20, pp. 1249–79

38. Anenberg SC, Schwartz J, Shindell D, Amann M, Faluvegi G, et al. 2012. Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environ. Health Perspect.* 120(6):831–39
39. Edenhofer E, Jakob M, Creutzig F, Flachsland C, Fuss S, et al. 2015. Closing the emission price gap. *Glob. Environ. Chang.* 31:132–43
40. McCollum DL, Krey V, Riahi K, Kolp P, Grubler A, et al. 2013. Climate policies can help resolve energy security and air pollution challenges. *Clim. Change* 119(2):479–94
41. Nemet GF, Holloway T, Meier P. 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environ. Res. Lett.* 5(1):014007
42. Pittel K, Rübbelke DTG. 2008. Climate policy and ancillary benefits: a survey and integration into the modelling of international negotiations on climate change. *Ecol. Econ.* 68(1–2):210–20
43. Rao S, Pachauri S, Dentener F, Kinney P, Klimont Z, et al. 2013. Better air for better health: forging synergies in policies for energy access, climate change and air pollution. *Glob. Environ. Change* 23(5):1122–30
44. Swart R, Amann M, Raes F, Tuinstra W. 2004. A good climate for clean air: linkages between climate change and air pollution: an editorial essay. *Clim. Change* 66(3):263–69
45. Barker T, Bashmakov I, Alharthi A, Amann M, Cifuentes L, et al. 2007. Mitigation from a cross-sectoral perspective. See Ref. 48, pp. 619–90
46. Holland SP. 2010. *Spillovers from climate policy*. Work. Pap. 16158, Natl. Bureau Econ. Res., Cambridge, MA
47. Jakob M, Edenhofer O. 2014. Green growth, degrowth, and the commons. *Oxf. Rev. Econ. Policy* 30(3):447–68
48. IPCC. 2007. *Climate Change 2007: Mitigation of Climate Change: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer. Cambridge, UK/New York: Cambridge Univ. Press
49. Hertwich E. 2014. Understanding the climate mitigation benefits of product systems: comment on "using attributional life cycle assessment to estimate climate-change mitigation…" *J. Ind. Ecol.* 18(3):464–65
50. Thompson W, Whistance J, Meyer S. 2011. Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions. *Energy Policy* 39(9):5509–18
51. Rajagopal D, Hochman G, Zilberman D. 2011. Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*. 39(1):228–33
52. Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, et al. 2014. Buildings. See Ref. 20, pp. 671–738
53. Azevedo IML. 2014. Consumer end-use energy efficiency and rebound effects. *Annu. Rev. Environ. Resour.* 39(1):393–418
54. Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, et al. 2014. Transport. See Ref. 20, pp. 599–670
55. Blanco G, Gerlagh R, Suh S, Barrett J, de Coninck HC, et al. 2014. Drivers, trends and mitigation. See Ref. 20, pp. 351–411
56. Victor DG, Zhou D, Ahmed EHM, Dadhich PK, Olivier JGJ, et al. 2014. Introductory chapter. See Ref. 20, pp. 111–50
57. van Vuuren DP, Cofala J, Eerens HE, Oostenrijk R, Heyes C, et al. 2006. Exploring the ancillary benefits of the Kyoto protocol for air pollution in Europe. *Energy Policy* 34(4):444–60

58. Shindell D, Kuylenstierna JCI, Vignati E, van Dingenen R, Amann M, et al. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335(6065):183–89
59. West JJ, Smith SJ, Silva RA, Naik V, Zhang Y, et al. 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nat. Clim. Change* 3(10):885–89
60. Burtraw D, Krupnick A, Palmer K, Paul A, Toman M, Bloyd C. 2003. Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector. *J. Environ. Econ. Manag.* 45(3):650–73
61. Klimont Z, Smith SJ, Cofala J. 2013. The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions. *Environ. Res. Lett.* 8(1):014003
62. Markandya A, Armstrong BG, Hales S, Chiabai A, Criqui P, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *Lancet* 374(9706):2006–15
63. Rose SK, Richels R, Smith S, Riahi K, Strefler J, van Vuuren DP. 2014. Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Clim. Change* 123(3–4):511–25
64. Smith KR, Haigler E. 2008. Co-benefits of climate mitigation and health protection in energy systems: scoping methods. *Annu. Rev. Public Health* 29(1):11–25
65. Haines A, McMichael AJ, Smith KR, Roberts I, Woodcock J, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet* 374(9707):2104–14
66. Goulder LH, Stavins RN. 2011. Challenges from state-federal interactions in US climate change policy. *Am. Econ. Rev.* 101(3):253–57
67. van Vuuren D, Kok M, eds. 2012. *Roads from Rio+20*: *Pathways to Achieve Global Sustainability Goals by 2050*. Hague, Neth.: PBL Neth. Environ. Agency
68. Amann M, Klimont Z, Wagner F. 2013. Regional and global emissions of air pollutants: recent trends and future scenarios. *Annu. Rev. Environ. Resour.* 38:31–55
69. Rogelj J, Schaeffer M, Meinshausen M, Shindell DT, Hare W, et al. 2014. Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *PNAS* 111(46):16325–30
70. Rafaj P, Schöpp W, Russ P, Heyes C, Amann M. 2013. Co-benefits of post-2012 global climate mitigation policies. *Mitig. Adapt. Strateg. Glob. Change* 18(6):801–24
71. Rafaj P, Bertok I, Cofala J, Schöpp W. 2013. Scenarios of global mercury emissions from anthropogenic sources. *Atmos. Environ.* 79:472–79
72. Bond TC, Doherty SJ, Fahey DW, Forster PM, Berntsen T, et al. 2013. Bounding the role of black carbon in the climate system: a scientific assessment. *J. Geophys. Res. Atmos.* 118(11):5380–552
73. Mahowald N, Ward DS, Kloster S, Flanner MG, Heald CL, et al. 2011. Aerosol impacts on climate and biogeochemistry. *Annu. Rev. Environ. Resour.* 36:45–74
74. Ramanathan V, Carmichael G. 2008. Global and regional climate changes due to black carbon. *Nat. Geosci.* 1(4):221–27
75. Smith SJ, Mizrahi A. 2013. Near-term climate mitigation by short-lived forcers. *PNAS* 110(35):14202–6
76. Bowerman NHA, Frame DJ, Huntingford C, Lowe JA, Smith SM, Allen MR. 2013. The role of short-lived climate pollutants in meeting temperature goals. *Nat. Clim. Change* 3(12):1021–24
77. Myhre G, Fuglestvedt JS, Berntsen TK, Lund MT. 2011. Mitigation of short-lived heating components may lead to unwanted long-term consequences. *Atmos. Environ.* 45(33):6103–6

78. Cherp A, Jewell J, Vinichenko V, Bauer N, DeCian E. 2016. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Clim. Change* 136:83–94
79. Criqui P, Mima S. 2012. European climate—energy security nexus: a model based scenario analysis. *Energy Policy* 41:827–42
80. Jewell J, Cherp A, Riahi K. 2014. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. *Energy Policy* 65:743–60
81. Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. 2009. Indicators for energy security. *Energy Policy* 37(6):2166–81
82. Shukla PR, Dhar S. 2011. Climate agreements and India: aligning options and opportunities on a new track. *Int. Environ. Agreem. Polit. Law Econ.* 11(3):229–43
83. Jewell J, Cherp A, Vinichenko V, Bauer N, Kober T, et al. 2013. Energy security of China, India, the E.U. and the U.S. under long-term scenarios: results from six IAMs. *Clim. Change Econ.* 4(4):1340011
84. Bauer N, Bosetti V, Hamdi-Cherif M, Kitous A, McCollum D, et al. 2015. CO_2 emission mitigation and fossil fuel markets: dynamic and international aspects of climate policies. *Technol. Forecast. Soc. Change* 90(Part A):243–56
85. Bauer N, Mouratiadou I, Luderer G, Baumstark L, Brecha RJ, et al. 2016. Global fossil energy markets and climate change mitigation—an analysis with REMIND. *Clim. Change* 136:69–82
86. Haurie A, Vielle M. 2010. A metamodel of the oil game under climate treaties. *INFOR Inf. Syst. Oper. Res.* 48(4):215–28
87. McCollum D, Bauer N, Calvin K, Kitous A, Riahi K. 2014. Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Clim. Change* 123(3–4):413–26
88. McGlade C, Ekins P. 2014. The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature* 517(7533):187–90
89. Tavoni M, Kriegler E, Aboumahboub T, Calvin K, De Maere G, et al. 2013. The distribution of the major economies’ effort in the Durban platform scenarios. *Clim. Change Econ.* 04(04):1340009
90. Johansson DJA, Azar C, Lindgren K, Persson TA. 2009. OPEC strategies and oil rent in a climate conscious world. *Energy J.* 30(3):23–50
91. Nemet GF, Brandt AR. 2012. Willingness to pay for a climate backstop: liquid fuel producers and direct CO_2 air capture. *Energy J.* 33(1):53–82
92. Persson TA, Azar C, Johansson D, Lindgren K. 2007. Major oil exporters may profit rather than lose, in a carbon-constrained world. *Energy Policy* 35(12):6346–53
93. Rozenberg J, Hallegatte S, Vogt-Schilb A, Sassi O, Guivarch C, et al. 2010. Climate policies as a hedge against the uncertainty on future oil supply. *Clim. Change* 101(3–4):663–68
94. Gracceva F, Zeniewski P. 2014. A systemic approach to assessing energy security in a low-carbon EU energy system. *Appl. Energy* 123:335–48
95. Bollen J, Hers S, van der Zwaan B. 2010. An integrated assessment of climate change, air pollution, and energy security policy. *Energy Policy* 38(8):4021–30
96. Jakob M, Steckel JC. 2014. How climate change mitigation could harm development in poor countries. *WIREs Clim. Change* 5(2):161–68
97. Kaundinya DP, Balachandra P, Ravindranath NH. 2009. Grid-connected versus stand-alone energy systems for decentralized power—a review of literature. *Renew. Sustain. Energy Rev.* 13(8):2041–50
98. van Ruijven BJ, Schers J, van Vuuren DP. 2012. Model-based scenarios for rural electrification in developing countries. *Energy* 38(1):386–97

99. Pachauri S. 2014. Household electricity access a trivial contributor to CO_2 emissions growth in India. *Nat. Clim. Change* 4(12):1073–76
100. Pachauri S, van Ruijven BJ, Nagai Y, Riahi K, van Vuuren DP, et al. 2013. Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* 8(2):024015
101. Rogelj J, McCollum DL, Riahi K. 2013. The UN's "sustainable energy for all" initiative is compatible with a warming limit of 2°C. *Nat. Clim. Change* 3(6):545–51
102. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, et al. 2014. Agriculture, forestry and other land use (AFOLU). See Ref. 20, pp. 811–922
103. Popp A, Rose SK, Calvin K, van Vuuren DP, Dietrich JP, et al. 2014. Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Clim. Change* 123(3–4):495–509
104. Rose SK, Ahammad H, Eickhout B, Fisher B, Kurosawa A, et al. 2012. Land-based mitigation in climate stabilization. *Energy Econ.* 34(1):365–80
105. Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, et al. 2009. Implications of limiting CO_2 concentrations for land use and energy. *Science* 324(5931):1183–86
106. Hoff H. 2011. *Understanding the nexus: background paper for the Bonn2011 nexus conference*. Bonn2011 Conference: the water, energy and food security nexus. Stockh. Environ. Inst., Stockholm
107. Howells M, Hermann S, Welsch M, Bazilian M, Segerström R, et al. 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Change* 3(7):621–26
108. Bazilian M, Rogner H, Howells M, Hermann S, Arent D, et al. 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39(12):7896–906
109. Bustamante M, Robledo-Abad C, Harper R, Mbow C, Ravindranat NH, et al. 2014. Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Glob. Change Biol.* 20(10):3270–90
110. Humpenöder F, Popp A, Dietrich JP, Klein D, Lotze-Campen H, et al. 2014. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.* 9(6):064029
111. Smith P, Haberl H, Popp A, Erb K, Lauk C, et al. 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* 19(8):2285–302
112. Lotze-Campen H, von Lampe M, Kyle P, Fujimori S, Havlik P, et al. 2014. Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agric. Econ.* 45(1):103–16
113. Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, et al. 2011. Bioenergy. In *Special Report on Renewable Energy Sources and Climate Change Mitigation*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, K Seyboth, P Matschoss, et al., pp. 209–331. Cambridge, UK/New York: Cambridge Univ. Press
114. Hejazi MI, Edmonds J, Clarke L, Kyle P, Davies E, et al. 2013. Integrated assessment of global water scarcity over the 21st century—Part 2: climate change mitigation policies. *Hydrol. Earth Syst. Sci. Discuss* 10(3):3383–425
115. Bonsch M, Humpenöder F, Popp A, Bodirsky B, Dietrich JP, et al. 2014. Trade-offs between land and water requirements for large-scale bioenergy production. *Glob. Change Biol. Bioenergy* 8(1):11–24
116. De Fraiture C, Giordano M, Liao Y. 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy* 10(Suppl. 1):67–81

117. Arnell NW, van Vuuren DP, Isaac M. 2011. The implications of climate policy for the impacts of climate change on global water resources. *Glob. Environ. Change* 21(2):592–603
118. GEA Writ. Team. 2012. *Global Energy Assessment: Toward a Sustainable Future.* Cambridge, UK/New York: Cambridge Univ. Press/Int. Inst. Appl. Syst. Anal.
119. McCollum DL, Krey V, Riahi K. 2011. An integrated approach to energy sustainability. *Nat. Clim. Change* 1(9):428–29
120. Chuwah C, van Noije T, van Vuuren DP, Hazeleger W, Strunk A, et al. 2013. Implications of alternative assumptions regarding future air pollution control in scenarios similar to the representative concentration pathways. *Atmos. Environ.* 79:787–801
121. Calvin K, Wise M, Kyle P, Patel P, Clarke L, Edmonds J. 2014. Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change* 123(3–4):691–704
122. Akimoto K, Sano F, Hayashi A, Homma T, Oda J, et al. 2012. Consistent assessments of pathways toward sustainable development and climate stabilization. *Nat. Resour. Forum* 36(4):231–44
123. Kainuma M, Shukla PR, Jiang K. 2012. Framing and modeling of a low carbon society: an overview. *Energy Econ.* 34(Suppl. 3):S316–24
124. Shukla PR, Chaturvedi V. 2012. Low carbon and clean energy scenarios for India: analysis of targets approach. *Energy Econ.* 34(Suppl. 3):S487–95
125. Shukla PR, Dhar S, Mahapatra D. 2008. Low-carbon society scenarios for India. *Clim. Policy* 8(Suppl. 1):S156–76
126. Strachan N, Foxon T, Fujino J. 2008. Low-carbon society (LCS) modelling. *Clim. Policy* 8(Suppl. 1):S3–4
127. Hourcade J-C, Crassous R. 2008. Low-carbon societies: a challenging transition for an attractive future. *Clim. Policy* 8(6):607–12
128. Amann M, Kejun J, Jiming H, Wang S, Xing Z, et al. 2008. *GAINS-Asia. Scenarios for Cost-Effective Control of Air Pollution and Greenhouse Gases in China.* Laxenburg, Austria: Int. Inst. Appl. Syst. Anal.
129. Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, et al. 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. *Environ. Model. Softw.* 26(12):1489–501
130. Anthoff D, Tol RS. 2009. The impact of climate change on the balanced growth equivalent: an application of fund. *Environ. Resour. Econ.* 43(3):351–67
131. Nordhaus WD. 2010. Economic aspects of global warming in a post-Copenhagen environment. *PNAS* 107(26):11721–26
132. Stern N. 2008. The economics of climate change. *Am. Econ. Rev.* 98(2):1–37
133. Krey V, Masera O, Blanford G, Bruckner T, Cooke R, et al. 2014. Annex II: metrics & methodology. See Ref. 20, pp. 1281–328
134. Lipsey RG, Lancaster K. 1956. The general theory of second best. *Rev. Econ. Stud.* 24(1):11–32
135. Babiker MH, Eckaus RS. 2007. Unemployment effects of climate policy. *Environ. Sci. Policy* 10(7–8):600–9
136. Guivarch C, Crassous R, Sassi O, Hallegatte S. 2011. The costs of climate policies in a second-best world with labour market imperfections. *Clim. Policy* 11(1):768–88
137. Goulder LH. 1995. Environmental taxation and the double dividend: a reader's guide. *Int. Tax Public Financ.* 2(2):157–83
138. Fullerton D, Metcalf GE. 2001. Environmental controls, scarcity rents, and pre-existing distortions. *J. Public Econ.* 80(2):249–67

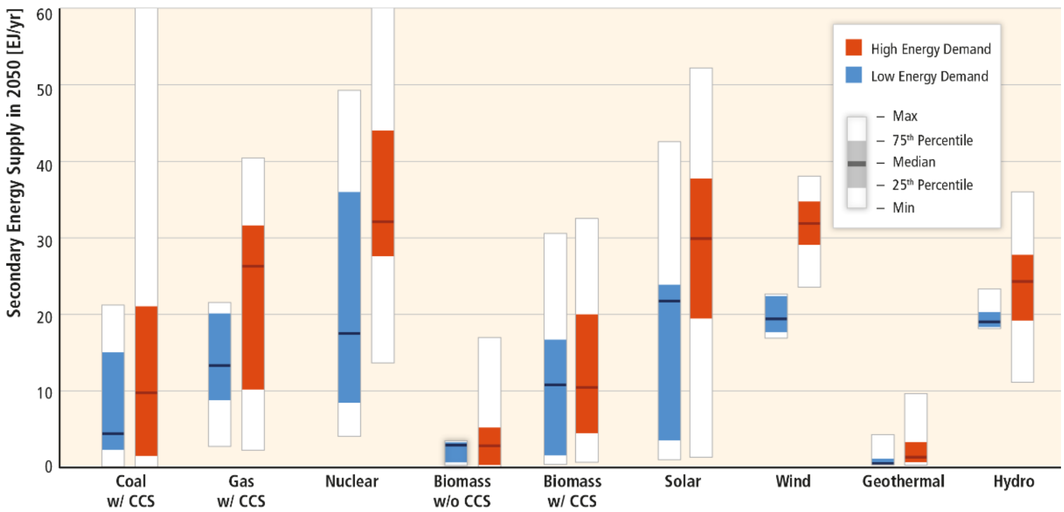
139. Patt AG, van Vuuren DP, Berkhout F, Aaheim A, Hof AF, et al. 2010. Adaptation in integrated assessment modeling: Where do we stand? *Clim. Change* 99(3–4):383–402
140. Bosello F, Carraro C, DeCian E. 2010. Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. *Clim. Change Econ.* 1(2):71–92
141. De Bruin KC, Dellink RB, Tol RS. 2009. AD-DICE: an implementation of adaptation in the DICE model. *Clim. Change* 95(1–2):63–81
142. DeCian E, Hof AF, Tavoni M, van Vuuren DP. 2015. Sharing the effort of mitigation, adaptation, and damages. *Environ. Res. Lett.* **11** 074015
143. Hof AF, den Elzen MG, van Vuuren DP. 2010. Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes. *Mitig. Adapt. Strateg. Glob. Change* 15(1):19–40
144. Stewart RB, Oppenheimer M, Rudyk B. 2013. A new strategy for global climate protection. *Clim. Change* 120:1–12
145. Parry I, Veung C, Heine D. 2014. *How much carbon pricing is in countries' own interests? The critical role of co-benefits.* CESifo Work. Pap. No. 5015, CESifo Group Munich. http://www.cesifo-group.de/de/ifoHome/publications/working-papers/CESifoWP/CESifoWPdetails?wp_id=19131827
146. Sarewitz D. 2004. How science makes environmental controversies worse. *Environ. Sci. Policy* 7(5):385–403
147. Fischedick M, Roy J, Abdel-Aziz A, Acquaye A, Allwood JM, et al. 2014. Industry. See Ref. 20, pp. 739–810
148. Cherp A, Adenikinju A, Goldthau A, Hernandez F, Hughes L, et al. 2012. Energy and security. See Ref. 118, pp. 325–84
149. Havlík P, Schneider UA, Schmid E, Böttcher H, Fritz S, et al. 2011. Global land-use implications of first and second generation biofuel targets. *Energy Policy* 39(10):5690–702
150. Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, et al. 2009. Indirect emissions from biofuels: how important? *Science* 326(5958):1397–99
151. Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, et al. 2012. Using land to mitigate climate change: hitting the target, recognizing the trade-offs. *Environ. Sci. Technol.* 46(11):5672–79
152. Rose SK, Kriegler E, Bibas R, Calvin K, Popp A, et al. 2014. Bioenergy in energy transformation and climate management. *Clim. Change* 123(3–4):477–93
153. Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, et al. 2013. A global water scarcity assessment under shared socio-economic pathway—Part 2: water availability and scarcity. *Hydrol. Earth Syst. Sci.* 17(7):2393–413

5.10 Supplemental material

5.10.1 Dealing with uncertainty in integrated model studies

The integrated model results presented in Sections 5.4 and 5.5 derive from large-scale numerical models that identify the globally most cost-effective portfolios of mitigation measures for a given climate goal for all world regions. To that end, they integrate insights from different disciplines and draw on models of both biogeophysical and human processes over long-time horizons (1–3). To circumvent climate system uncertainties with respect to the temperature response due to a given emission scenario, integrated models usually calculate mitigation scenarios whose emission pathways meet different atmospheric CO_2eq concentrations or carbon budgets. The uncertainty reflected in their results due to the diversity of modeling approaches with respect to structural as well as parametric differences (4) is hence distinct from the uncertainty of the exact change in the global mean surface temperature due to different emission scenarios (see Section 6.3.2.6 in 5). The model community regularly organizes model intercomparison projects in which efforts have been made to harmonize key input parameters and to make model outputs comparable (4, 6–10). Partly owing to this coordinated research agenda, the results from the different modeling teams have been an important contribution to the IPCC Assessment Reports (e.g., 5, 11, 12). Another reason is that cost-benefit analysis (CBA) is contested in climate economics due to a variety of reasons, one of them being the challenge to adequately account for 'fat tail' probability distributions of high-impact climate damages, as discussed in Edenhofer et al. (3). There are, of course, a number of drawbacks associated with the global approach taken by the models. For example, many non-technical measures including behavioural changes or modal shift are usually not represented in detail by integrated models (13). In some circumstances, multi-criteria analysis (MCA) approaches might instead be chosen to make synergies and trade-offs across different objectives transparent without valuation in monetary terms (14–17).

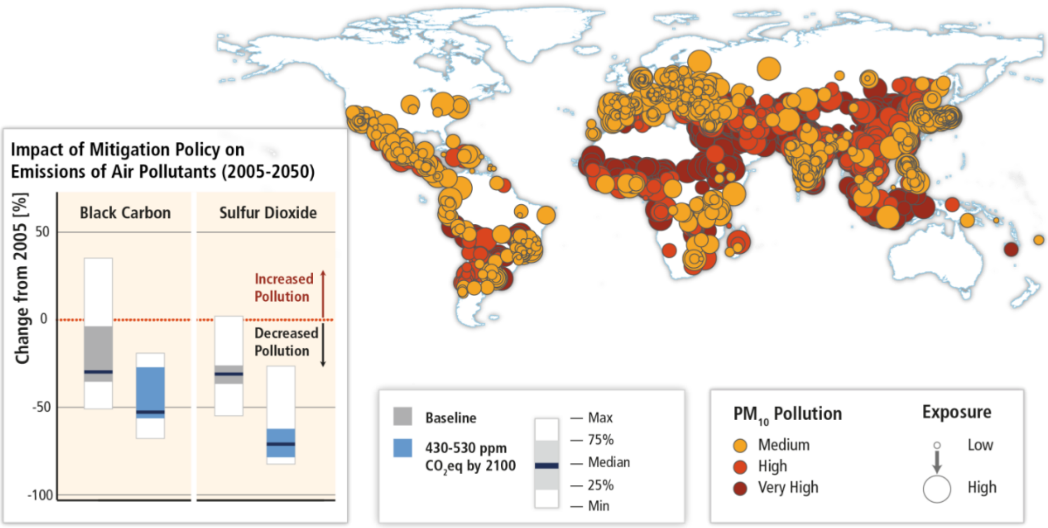
Although the deployment projections from the integrated model literature for the portfolio of measures are consistent with a particular mitigation goal, such as a given atmospheric CO_2eq concentration, they are uncertain with respect to the role of individual measures. This is illustrated by Supplemental Figure S-5.1 which shows results from mitigation scenarios leading to an atmospheric concentration of 430-530 ppm CO_2eq in 2100, i.e., with a probability of roughly 50% and higher of staying below the 2°C target. The figure does show, however, how the two main mitigation strategies, energy demand reduction and switching to low-carbon fuels, interact on a global scale (see also Sections 5.3 and 5.5): the required upscaling of low-carbon energy supply technologies for meeting a stringent mitigation goal is significantly lower for future scenarios in which the total final energy demand is low. Reducing energy demand (against baseline) is increasingly seen as a low-cost mitigation strategy within the integrated model literature (e.g., 4, 9, 18).



Supplemental Figure S-5.1 Deployment of low-carbon energy supply technologies in 2050 for mitigation scenarios reaching 430-530 ppm CO_2-equivalent (CO_2eq) concentration in 2100, differentiating between low- and high-energy demand scenarios. Blue (red) bars show the deployment range with <20% growth of final energy in 2050 compared to 2010 (>20% growth of final energy in 2050 compared to 2010). For each technology, the full deployment range, the interquartile and the median are displayed (adapted from 19).

This is also why the model teams have constructed low-EI pathways in addition to the conventional 'scenarios families' (i.e., scenarios where some political and/or technological aspects are constrained allowing comparison across models for similar sets of assumptions). In that way, it is possible to analyze implicitly how different energy demand patterns (e.g., through behavioural changes in energy service, food and material consumption) in the future can impact mitigation efforts in terms of timing, costs and effects on the rest of the energy system. Since the cost-effective mitigation potential of energy efficiency improvements declines, however, with increasing decarbonization of the supply side, they need to be realized in the short to medium term if targeted at mitigation (13).

Supplemental Figure S-5.2 provides an illustrative example for the co-benefits of stringent mitigation policies for air pollutant emissions. It shows the spatial distribution of the current human exposure to PM_{10} pollution in 3200 cities, as well as the ranges of co-benefits for two key air pollutants (SO_2 and BC) from a large number of mitigation scenarios from the WGIII AR5 scenario database. Despite relatively large uncertainties (partly owing to parametric and structural differences across integrated models, see above), the co-benefits are robust against a wide range of integrated models that quantified the climate-pollution interactions.



Supplemental Figure S-5.2 Human risk exposure to PM10 pollution in 3200 cities worldwide (adapted from 20, data from 21) and co-benefits of stringent mitigation policies for air quality in scenarios reaching concentrations of 430-530 ppm CO_2eq in 2100 (adapted from 5).

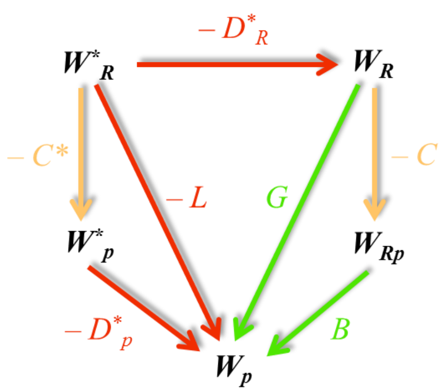
5.10.2 A conceptualization of welfare metrics in integrated model studies

To conceptualize the diverse set of cost information from integrated models in a welfare framework, it is useful to rewrite the social welfare function from Section 5.2 as $W(z_1^* - D_1(\boldsymbol{p}), \dots, z_m^* - D_m(\boldsymbol{p}), c(\boldsymbol{p}))$, where the objective z_i is described as the combination of some ideal level z_i^* in the counterfactual case of a non-existing policy problem, e.g., an undamaged environment, and the adverse impact D_i on the objective z_i under some set of given policies $\boldsymbol{p}$. In addition, we add household consumption c that may be directly affected by the policy implementation as a further element of the welfare function. The counterfactual reference case without policy intervention is then characterized by welfare W_R for some reference policy $\boldsymbol{p}_R$, and the total welfare gain of a policy intervention $d\boldsymbol{p} = \boldsymbol{p} - \boldsymbol{p}_R$ is given by $G = W_p - W_R$. Thus, the welfare differentials shown in Supplemental Figure S-5.3 could be based on direct welfare, welfare equivalent consumption metrics, direct consumption, economic output and partial equilibrium measures depending on the model.

$$W_p = W(z^*_1 - D_1(\boldsymbol{p}), \dots, z^*_m - D_m(\boldsymbol{p}), c(\boldsymbol{p}))$$
$$W_R = W(z^*_1 - D_1(\boldsymbol{p}_R), \dots, z^*_m - D_m(\boldsymbol{p}_R), c(\boldsymbol{p}_R))$$
$$W_{Rp} = W(z^*_1 - D_1(\boldsymbol{p}_R), \dots, z^*_m - D_m(\boldsymbol{p}_R), c(\boldsymbol{p}))$$
$$W^*_p = W(z^*_1, \dots, z^*_m, c(\boldsymbol{p}))$$
$$W^*_R = W(z^*_1, \dots, z^*_m, c(\boldsymbol{p}_R))$$

Damages (in reference case): $D^*_R = W^*_R - W_R$
Damages (in policy case): $D^*_p = W^*_p - W_p$
Policy costs (CEA without damages): $C^* = W^*_R - W^*_p$
Policy costs (at reference damages): $C = W_R - W_{Rp}$
Policy benefits: $B = W_p - W_{Rp}$

Welfare gain from policy intervention: $G = W_p - W_R$
Residual welfare loss of policy problem: $L = W^*_R - W_p$



Supplemental Figure S-5.3 Welfare and associated cost and benefit metrics for transformational policy analysis with integrated models.

5.10.3 Key characteristics of integrated models with respect to multiple objectives

In order to provide an overview of the types of integrated models on which the literature builds that is reviewed and condensed in Sections 5.10.4 and 5.10.5, Supplemental Table S-5.1 provides key characteristics of a representative set of six different integrated models with a special focus on the differences discussed in Section 5.10.4.3:

1. the coverage of policy impact channels is represented by the columns 'System boundaries' and 'Non-climate sustainability objectives covered';
2. the degree to which (changes in) welfare can be measured is represented by the columns 'Model type', 'Metric for climate change mitigation costs', and 'Costs for other objectives covered'.

One aspect not covered by the above conceptualization is the interrelation between climate change mitigation and poverty eradication beyond access to basic energy needs. Generally, current integrated models are lacking the presentation of the poor and their economic and social development. Conversely, climate policies are expected to have repercussions for development and poverty (22, 23). For example, higher energy prices could delay structural changes and the build-up of physical infrastructure (24, 25). The subset of integrated models which include an economic feedback capture some of these dynamics, although in most models economic growth is largely exogenous and stems mostly from labour productivity changes. Further endogenization of economic growth and linkage to poverty and climate change is an important avenue of future research.

Supplemental Table S-5.1 Key characteristics of and representation of multiple objectives and costs for selected global integrated modeling frameworks (partly derived from 26)

Model name	Model type	Metric for climate change mitigation costs	System boundaries	Non-climate sustainability objectives covered	Costs for other objectives covered
IMAGE	Energy system partial equilibrium model – recursive dynamic, simulation	Energy system cost mark-up, area under marginal abatement cost curve	Energy, land-use change, agriculture, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, biodiversity loss, energy security	Food production costs, energy access investments and subsidies, energy system costs for improving energy security
GCAM		Energy system cost mark-up, area under marginal abatement cost curve	Energy, land-use change, agriculture, forestry, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, energy security	Food production costs, energy system costs for improving energy security
MESSAGE-GLOBIOM	Systems engineering energy system model coupled with macroeconomic generable equilibrium model – perfect foresight, optimization	GDP & consumption loss, energy system cost mark-up, area under marginal abatement cost curve	Energy, land-use change, agriculture, forestry, climate, water for irrigation and energy, some adaptation (mainly in the agriculture sector)	Energy access, food, water, air pollution/health, energy security	Food production costs, energy access investments and subsidies, air pollution control costs (ex-post), energy system costs for improving energy security
REMIND-MAgPIE	Optimal growth generable equilibrium model – perfect foresight, optimization	Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, land-use change, agriculture, climate, air pollution, hydrology, some adaptation of land use (not comprehensive)	Food, water, air pollution, energy security	Food production costs, energy system costs for improving energy security, adaptation costs
WITCH-GLOBIOM		Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated land-use change, agriculture, forestry, climate, climate damages and adaptation	Food, air pollution, energy security, adaptation	Food production costs, energy system costs for improving energy security
GEM-E3	Computable Generable Equilibrium model – recursive dynamic, optimization	Welfare change, GDP & consumption loss, equivalent variation	Energy, climate, adaptation, labour markets	Air pollution, energy security, employment, impact on competitiveness	Energy system costs for improving energy security

5.10.4 Literature review of co-effects of mitigation measures in specific sectors

5.10.4.1 Energy supply

The energy supply sector is characterized by a chain of processes, comprising energy extraction, conversion, storage, transmission, and distribution processes. It is by far the largest contributor to GHG emissions, accounting for about 35% of the total anthropogenic GHG emissions at 144 $GtCO_2$/yr in 2010 (19). Between 2000 and 2010, their growth in the global energy supply sector increased to 3.1% per year, compared to the previous decade's levels of 1.7% – largely fueled by higher energy demand associated with rapid economic growth in emerging economies and an increase of the share of coal in the global fuel mix (27, 28).

As outlined in Bruckner et al. (19), multiple options exist to reduce energy supply sector GHG emissions. These include energy efficiency improvements and fugitive emission reductions in fuel extraction as well as efficiency improvements in energy conversion, transmission, and distribution systems; fossil fuel switching; and low-GHG energy supply technologies such as renewable energy (RE), nuclear power, and fossil fuel and bioenergy use with carbon dioxide capture and storage (CCS/BECCS). The implementation of these options can lead to a range of co-benefits and adverse side-effects that would have an influence on investment decisions, individual behaviour as well as policy directions (19, 29). The large variation that exists across and within regions in terms of the nature and composition of the co-effects can be explained by differences in resource endowments, renewable energy potential, economic structure, development pathways and priorities, etc.

Since changing the energy sector is at the heart of all climate change mitigation scenarios, there are always energy security co-effects from mitigation. Most energy security analysis focuses on short-term evaluation of static energy systems and even in the short-term, the meaning of energy security is contested (30–33). The most general definition, which is applicable under radical energy system transformations, is low vulnerability of vital energy systems (34), since both vulnerabilities and vital energy systems can change under mitigation scenarios (35). This definition also facilitates the identification of vital energy systems for different actors such as reliability of energy imports for importers (security of supply) and energy export revenues for energy exporters (security of demand) (36). The explicit separation of vital energy systems and vulnerabilities also helps identify distinct perspectives on risks and resilience capacities of energy systems. There are three commonly recognized perspectives on energy security: two focus on risks (sovereignty threats from foreign actors and robustness risks from critical infrastructure or resource constraints) and the third focuses on the resilience capacity, which is commonly measured by the diversity of an energy system (37). In general, the increase in renewables under mitigation scenarios leads to lower energy imports (35, 38–41) and higher resilience from greater energy system diversity (35, 38, 42, 43), but the existing literature has yet to develop a full analysis of the robustness impacts of scaling up renewables.

Another co-effect in the energy supply sector associated with climate policies is the effect they would have on employment. According to Cai et al. (44), the increased share of renewables in China generated over 470,000 net job gains in 2010. Studies by Lehr et al. (45) and Ruiz-Romero et al. (46) for Germany and Spain, respectively, also indicated over 500,000 people would be employed in the renewable energy supply sector in each country by 2030. Employment generation is not limited to the renewables sector. It also extends to nuclear power generation and CCS where safe-guarding jobs in the fossil-fuel industry is seen to be the main employment co-benefit (47, 48). However, it is also important to recognize that mitigation measures could come at a high cost when seen as unit of public investment against the number of jobs created. A study by Frondel et al. (49) has calculated that the cost per job created in the PV sector in Germany could be as high as €175,000, indicating that the viability of the industry is dependent on the level and continuity of public support (50).

Differences in access to modern energy supply across regions partly explain the wide disparity in economic and social development, both within and between countries. More than 1.3 billion people worldwide, especially in sub-Saharan Africa and developing Asia lack access to electricity and over 2.5 to 3 million people are estimated to lack modern fuels for heating and cooking (51, 52). Whilst improvements in energy access do not need to entail significant changes in GHG emissions (see Section 5.4.1), multiple co-benefits could be obtained. In a number of developing countries such as India, Brazil, Nepal and parts of Africa, renewable energy deployment has been shown to stimulate local economic development (53, 54). Educational benefits and enhanced support for income generation are some of the specific benefits observed in large parts of the developing world (55–57). At the same time, the effect of climate policies on energy prices and, by extension, energy access aspirations is not as clear and depends importantly on the specific circumstances within countries and devolved jurisdictions, such as the type of fuel used by different income groups, the distribution of the revenues through, e.g., a carbon tax and effectiveness of pro-poor interventions (58). Hence, regulators have an important role to play so that climate policies do not become a burden on low-income households and communities (19).

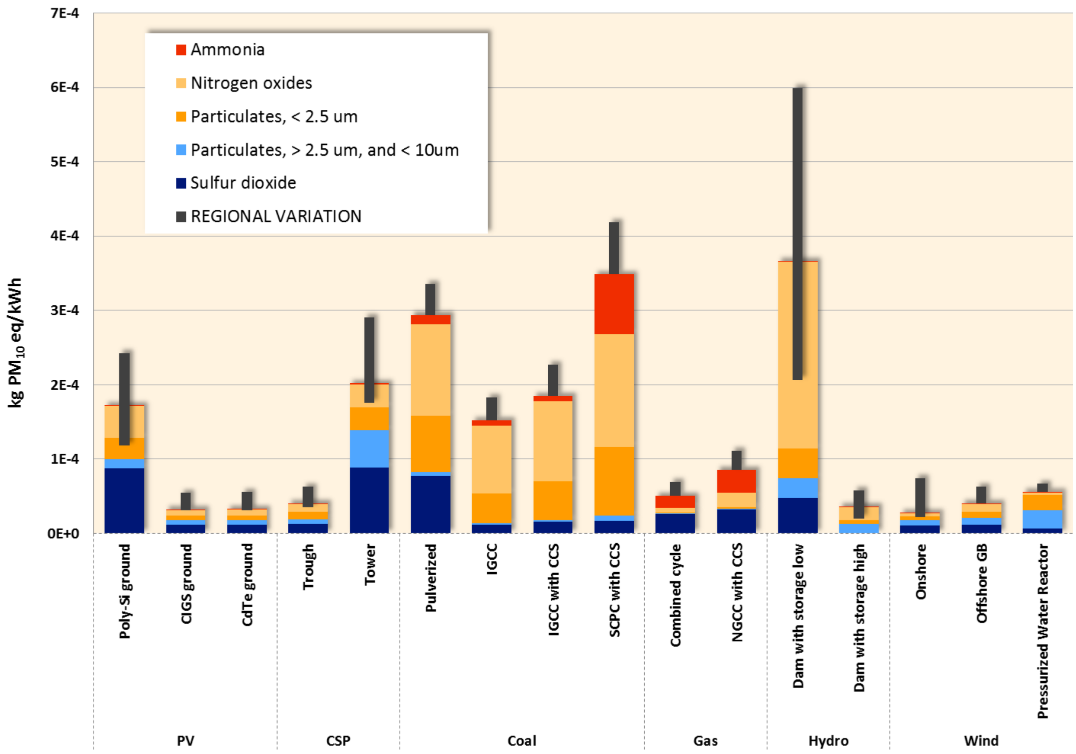
Combustion-related emissions from the energy supply sector cause significant and widespread human health and ecological impacts and depend on the height of the smokestack, the type of fuel used, the scrubber technology installed, the downwind population concentration as well as the background pollution from other sources (see Section 5.3). Ambient air pollution for some 80% of the world's population is estimated to exceed the World Health Organization (WHO) recommended levels of 10μg/m^3 for $PM_{2.5}$ (59) and to cause about 3.2 million of premature deaths each year (60). SO_2 and NO_x are implicated in acidification of fresh water and soils as well as threatening biodiversity (61, 62). Coal is an important source of mercury and other toxic metals, which could be reduced significantly through a range of pollution control technologies. Moreover, extraction and transport of fossil fuels, particularly coal, have high occupational impacts and accident rates (63). Replacing coal with cleaner fuels is hence associated with a wide range of co-benefits (19, 64).

However, ecological and health impacts are not limited to fossil fuels but also extend to renewable and nuclear systems. These impacts are in areas of land use, water use and pollution, effect on ecosystems, and impacts associated with mining and material processing. Hertwich et al. (65) compared indicators for pollution-related health and ecological effects of fossil fuel and renewable power technologies, taking into account life-cycle emissions and thus accounting for emissions from material and fuel production, manufacturing, operation and decommissioning. They found that although wind power, photovoltaics, concentrating solar power and some hydropower plants require more materials than coal and gas fired power plants, the pollution-related indicators are generally significantly lower for these renewable power technologies. Even modern supercritical coal power plants and natural gas combined-cycle plants with state-of-the-art pollution control equipment cause more PM exposure and freshwater ecotoxicity per kWh electricity produced than any of the renewable power technologies investigated (see Supplemental Figure S-5.4). For freshwater eutrophication, natural gas performed on par with renewable technologies, but it caused more marine eutrophication. The implementation of a range of renewables as foreseen in mitigation scenarios would stabilize or reduce all investigated pollution-related environmental and human health indicators, while a baseline scenario would increase these indicators (65). For impacts related to habitat change, see below.

Health effects associated with radioactive material handling have preoccupied healthcare professionals as some epidemiological studies show an increase in childhood leukaemia of populations living within 5 km of nuclear power plants (66–68).

The capture and storage of CO_2 from fossil fuel and biomass conversion processes are mitigation measures that are important in most mitigation scenarios investigated by the WGIII AR5 (19). Even though a wide range of technologies have been investigated, the process of CO_2 capture and storage requires 16-44% of additional energy (74), thereby increasing the fuel requirements and associated environmental impacts. On the other hand, CO_2 capture requires a pure gas stream, reducing some air pollution from the power plant. Investigating different CCS technologies, Hertwich et al. (65) find that CCS increases the life-cycle indicators for PM, toxicity and eutrophication by 5-60% compared to state-of-the-art coal and gas power plants. CCS doubles the demand for metals. For the case of biomass co-firing with coal, Schakel et al. (75) find that impacts from the biomass supply chain are comparable to those of coal production and that combustion-related pollution is also comparable, so that BECCS, while providing net negative GHG emissions, results in similar pollution-related health and ecological impacts as coal power with CCS.

Renewable energy systems are also in focus because they lead to habitat change, leading to biodiversity loss. For wind power, collisions of birds and bats with wind power plants are an important concern (76–78). It is clear that wind power plants reduce survival rates of some species, but there are disagreements as to whether these impacts are significant and how they compare to other threats to the same species (79, 80). For hydropower, dams clearly impact freshwater species by disrupting the free flow of water, affecting flooding and nutrient deposition, leading to a deepening of the channel, and acting as a migration barrier (81–83). Not all dams are used for hydropower and some hydropower plants may have positive impacts on freshwater species as well, and some impacts may at least be partially mitigated. For both hydropower and wind power, site selection, project design and mitigation of ecological impacts are important topics. Even though habitat change-related impacts of renewable energy sources can be clearly identified, it is not clear how these impacts compare with the ecological impacts of fossil fuel extraction, transport and use. Land use associated with coal mining is substantial and larger on a per kWh basis than that of most non-biomass renewable energy systems (65). Consumptive water use of hydropower and concentrating solar power is significant while that of photovoltaics and wind energy is small (84). The cooling water use of thermal power plants, whether they are operated with coal, nuclear or geothermal energy, can cause ecological impacts (85). CCS technologies can significantly increase water consumption and withdrawal (up to 100%) due to efficiency penalties and additional process demands (84, 86). Methods to compare such impacts are currently under development, but more work, taking into account site-specific impacts of populations of realized or prospective projects, is needed to allow a comparison of the ecological impacts of different energy scenarios.



Supplemental Figure S-5.4 Human health impact from PM exposure resulting from air pollution caused in the production of 1 kWh of electricity with various technologies Hertwich et al. (65) as evaluated using the lifecycle impact assessment method ReCiPe (http://www.lcia-recipe.net), presented in units of kg PM10-equivalents (PM_{10}-eq) as suggested by van Zelm et al. (69). Figure credit: Thomas Gibon, NTNU.

5.10.4.2 Bioenergy supply

Bioenergy mitigation options include energy resources as dedicated agricultural and/or forestry plantations, optimal forest harvesting, forest and agriculture residues or organic waste. A further mitigation option in this sector is given by reducing traditional biomass demand and/or increasing efficiency of bioenergy technologies (87, 88). Due to the different bioenergy sources as well as to the specificities of the areas where bioenergy is produced, development impacts from bioenergy and its qualification as potential co-benefits or adverse side-effects are context-, pace- and size-specific (88–91).

The specific interaction between environmental, social, institutional and technological factors with a given biomass resource and its size is what determines the sustainable development (SD) impacts in a given region. Further, co-benefits and potential adverse side-effects do not necessarily overlap, neither geographically nor socially (92–94). Thus generalizations (global statements) of SD impacts from a given bioenergy source is very difficult. Scientific studies since 2007 have looked at development impacts at five dimensions: institutional, social, environmental, economic and technological (see Supplemental Table S-5.2).

The main potential co-benefits seem to be related to access to energy services and impacts on the economy, job creation and improvement of local resilience (98–102). The main potential adverse side-effects of bioenergy include competition on arable land (103) and consequent impact on food security, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water and soil or increment in vulnerability to climate change (87, 90, 98, 99, 104–113). Research on indirect effects (e.g., those on consumption due to increased income) is only starting (114–117) and preliminary conclusions are not yet generalizable.

Labelling, certification and other information-based instruments are seen as option to promote 'sustainable' biofuels (91, 118). Nevertheless, certification approaches have been scrutinized and challenged on the basis of a lack of legitimacy in their design, inherent design weaknesses (119), and a deficient on-the-ground implementation (120, 121), rendering them inadequate substitutes for effective territorial policy frameworks.

For many bioenergy options and almost all regions there is still a knowledge gap between top-down models based on rough estimations and bottom-up studies looking at specific impacts on specific contexts (see, e.g., 95, 96, 122, 123).

Supplemental Table S-5.2 Major SD impacts – positive (+) and negative (-) – reported from bioenergy supply (based on 88, 95–97).

Institutional	Social	Environmental	Economic	Technological
May contribute to energy security (reduce dependency on fossil fuels) (+)	Land use competition implying risks, e.g., to food security (except for bioenergy derived from residues, wastes or by-products) (-) Some agroforestry plantations can contribute to food security while producing biomass resources (+)	Biofuel plantations can promote deforestation and/or forest degradation (-)	Increase in economic activity and income diversification (+) May promote concentration of income and /or increase poverty (-)	Can promote technology development and/or facilitate technology transfer (+)
Impacts on land tenure for local stakeholders (+/-, however mostly negative)	Increasing (+) or decreasing (-) existing conflicts or social discomfort	Increase in use of fertilizers with negative impacts on soil and water (-)	Increase (+) or decrease (-) of market opportunities	Increasing infrastructure coverage (+) while reduced access to infrastructure might increase marginalization (-)
Cross-sectoral coordination (+) or clashes (-) between forest sector, agriculture, energy and/or mining	Impacts on traditional practices (+/-) Promote capacity building and new skills (+)	Large-scale bioenergy crops can have negative impacts on soil quality, water pollution and biodiversity (-)	Contribution to the changes in prices of feedstock (+/-)	High-tech and/or mechanization might reduce labour demand (-) or promote capacity building (+)
Impacts on labour rights across the value chain (+/-)	Displacement of small-scale farmers by big-scale producers (-)	Displacement of activities or other land uses (+/-, however mostly negative)	Employment creation (+)	High dependence on technology transfer and/or technology acceptance (+/-)
Promotion of participative mechanisms for small scale producers (+/-)	Health impacts from bioenergy production (+/-, however mostly negative)	Installing bioenergy plantations on degraded land can have positive impacts on soil and biodiversity (+)	Bioenergy from waste and residues might create socio-economic benefits with reduced non-environmental risks (+)	
	Gender impacts (+/-)		Price uncertainty (+/-)	

5.10.4.3 Urban transport

Transport is relatively unique among the energy end-use sectors as it depends on petroleum products to 94%, with natural gas, biofuels and electricity making up the small rest (124). However, the modes with which people and freight are transported vary greatly with regard to their energy intensity, ranging from walking and cycling to shared modes, such as public transport to car and truck-based road transportation, rail, waterborne transport and aviation. The choice of modes, technologies and fuels heavily influences the potential externalities of passenger and freight transport. Air quality, safety, energy efficiency, access to mobility services and other factors that are considered to be co-benefits of sustainable transport measures from a climate change perspective are in fact often the driving factors for policy intervention, in particular on the local level.

As transport relies almost entirely on petroleum products, energy security is a major issue for the sector (30, 125, 126). While there is hence a direct link between energy security and mitigation actions that all reduce fuel consumption, potential co-benefits for other objectives differ across the types of action. For example, fuel switching and propulsion technology-based options, such as biofuels and electrification can potentially result in co-benefits for energy security, depending on the fuel stock or electricity source (35, 127, 128). These strategies, however, do not yield the potential to generate as many co-benefits for other objectives as many demand-side measures do (129). For example, fuel efficiency, shifting to more efficient transport modes and compact urban design can improve energy security (30, 32, 130) as well as access to mobility services and reduce transport costs, which positively affects productivity and social inclusion (131, 132) and provide better access to jobs, markets and social services (133–135).

Mitigation actions that relieve congestions are also a potential generator for additional co-benefits, providing that the reduced congestion does not induce additional traffic.[23] For congestion relieve measures to be effective a combination of solutions is vital to avoid trade-offs and induced additional travel. For example, 'Intelligent Transport Systems' and traffic management systems should be accompanied by strategies to shift to lower-carbon modes, such as walking, cycling and public transport. Technology and fuel-based measures are unlikely to impact congestion levels and traffic flows, indicating that these actions should also be part of a wider, more comprehensive strategy (141, 142).

Another major factor where climate change mitigation actions can have positive synergies with other objectives is related to the various health impacts of transport activities, such as air pollution, noise, vibration and road safety. Well over one million people are killed in road accidents globally each year, 91% of which occur in low and middle-income countries (143). Reducing car-based transport can have an immediate effect on road safety (144–147). Comparing the multiple health and safety effects of increased physical activity through walking and cycling with often higher exposure to air

[23] Time lost in traffic was valued at 1.2% of GDP in the UK (136); 3.4% in Dakar, Senegal; 3.3% to 5.3% in Beijing, China (137); 1% to 6% in Bangkok, Thailand (138) and up to 10% in Lima, Peru with daily travel times of almost four hours (139, 140).

pollution is slightly more complicated (147, 148), but the effects are considered to be mostly positive (145, 146). Again, a combined approach, for example in conjunction with fuel or technology switch for the public transport and taxi fleets, access restriction for road freight carriers and incentives for more efficient and lower-carbon motorized transport can ensure that air quality is improved to reduce exposure to air pollutants while using active modes of transport (149).

Biofuels for transportation as replacement for petroleum products are associated with several uncertainties, not only with regard to their ability to contribute to GHG emission reductions, but also to their air quality and health impacts (88). For example, replacing fossil-based transport fuels with biofuels may reduce carbon monoxide and hydrocarbon emissions but increase NO_x emissions (73). This is likely to improve, however, with more advanced biofuels (150). Similarly, the potential contribution of electric mobility to local air quality improvements depends on the source of the electricity generation and the location of power plants in a city (151).

There is a lack of studies managing to provide a comprehensive picture on the costs, benefits and potential adverse side-effects and co-benefits of sustainable transport measures across a range of options and beyond specific case studies. Some of those case studies are widely used as examples of the potential for co-benefits and synergies (e.g., 137, 147, 148, 152). Measuring the co-benefits and adverse side-effects of sustainable transport measures is currently not carried out in a consistent manner as different studies/countries apply different metrics and values, e.g., value of a statistical life vs. DALY/QALY or value of travel time, and are hence challenging to aggregate globally. Some effects are barely assessed at all, such as quality of life in cities, but can be very crucial for the success of a sustainable urban mobility policy (see also 20 for a spatial planning perspective on transit and accessibility).

5.10.4.4 Buildings

The buildings sector is characterized by the utilization of a diverse array of energy sources, technologies and practices, which provide a number of energy services, namely thermal comfort, refrigeration, illumination, communication and entertainment, sanitation and hygiene, nutrition, etc. The technologies and practices widely used today in the buildings sector rely, directly or indirectly, on the usage of various energy carriers, such as solid fuels (3%), petroleum products (13%), natural gas (24%), combustible renewable energy sources (31%) as well as electricity (29%) and are to a large extent responsible for a number of negative impacts to the environment and public health (153). Specifically:

1. In developing countries inefficient combustion of traditional solid fuels used by about 2.5-3 billion people in households worldwide (51, 154), mainly biomass and coal, produces gaseous and particulate emissions (known as products of incomplete combustion), which result in significant health impacts, particularly for women and children who spend longer periods at home (155–157). Indoor air pollution from the use of biomass and coal was responsible for about 3.5 million premature deaths in 2010 (60).

2. A significant part of the population in both developed and developing countries lives in households with inadequate insulation, ventilation and heating systems; the resulting indoor conditions are associated with respiratory diseases, allergies, asthma, etc. (158, 159). Of particular importance is fuel poverty, which is associated with excess mortality and morbidity effects, depression and anxiety. It is estimated that over 10% to as much as 40% of excess winter deaths in temperate countries is related to inadequate indoor temperatures (160, 161).

3. The consumption of fossil fuels either directly in households or indirectly through electricity and heat generation is associated with the degradation of outdoor air quality, resulting in: (i) increased mortality and morbidity, particularly in developing countries and big cities (60, 162, 163); and (ii) additional stresses on natural and anthropogenic ecosystems (19, 164).

The implementation of energy efficiency measures in the buildings sectors, including fuel switching to electricity that is increasingly decarbonized, improves indoor and outdoor conditions resulting in significant co-benefits for public health and the environment. For example, the associated health and environmental benefits attributed to reduced outdoor air pollution are of the order of 8-22% of the value of energy savings in developed countries (165, 166), and even higher in developing countries. Monetized co-benefits associated with fuel poverty alleviation make up over 30% of the total benefits of energy efficiency investments (160, 167). Bruce et al. (168) found that the healthy years gained per US$2010 million spent in implementing interventions aiming at reducing indoor air pollution range between 700 and 79,500 depending on the world region and the type of intervention implemented. On the other hand, the implementation of energy efficiency technologies in the building sectors is associated with limited risks emanating mostly from health problems caused by airtight buildings with insufficient ventilation ('sick building syndrome') and the use of sub-standard energy efficiency technologies due to in-situ toxic chemicals (169, 170).

Apart from health and environmental improvements, an increasing number of studies show that greater use of renewables and energy efficiency technologies in the building sectors result in positive economic effects through job creation, economic growth, increase of income and reduced needs for capital stock in the energy sector (171–173); these conclusions, however, have been criticized for the accounting methods used, whereas objections have been raised over the overall efficacy of using public funds for implementing energy projects instead of other less labour-intensive activities (174). A review of the literature on quantifications of the employment effects of energy efficiency measures in the buildings sector conducted in the context of WGIII AR5, point out that the implementation of mitigation measures in buildings in the developed economies generates on average 13 (with a range of 0.7 and 35.5) job-years per $ million spent (175). Monetization of employment effects for integrating them in social CBA is possible through the implementation of either the adjusted reservation wage gain approach or the adjusted earnings gain approach (176). A recent application of the latter showed that the employment benefits associated with the exploitation of energy saving technologies in the Greek building stock reach 10-24% of the energy costs savings attributed to the implementation of these interventions throughout their entire lifetime, increased up to 45% in economies with high unemployment rates (177). In addition, energy-related renovations of buildings improve workplace productivity by 1-9% or even higher for specific activities or case studies as evidenced by a meta-analysis of several studies undertaken in the context of WGIII AR5 (see 159, 169, 175, 178).

Other co-benefits associated with the implementation of energy efficiency measures in the buildings sector comprise improved energy security, increased comfort due to better control of indoor conditions and the reduction of outdoor noise, increased safety, enhancement of urban biodiversity, reduction of the heat island effect, improved values for real estate and enhanced ability to rent (20, 175). It should also be noted that most of the aforementioned co-benefits are also expected from fuel switching to electricity that is increasingly decarbonized. Increased use of electricity in the building sector is projected in both baseline and mitigation scenarios elaborated (175); however, the magnitude of the associated health and environmental benefits are related to the nature of electricity generation (see Supplemental Material Section 5.10.4.1).

Despite the unequivocal progress in quantifying the co-benefits of energy efficiency measures there are only a limited number of studies that incorporate such benefits into social CBA; using common metrics and monetization could facilitate their integration into decision-making processes. In most cases the quantified co-benefits (in physical or monetary terms) of energy efficiency are expressed per million investments in energy-saving interventions or per unit of energy saved by the implementation of such interventions (179). However, the utilization of these indices in different case studies is not easy as the mitigation potential per intervention and the other underlying assumptions may differ significantly from country to country or even within a given country. Finally, while these metrics do not lend themselves to cross-sectoral analysis, they can be very policy-relevant in specific policy settings.

5.10.4.5 Industry

The industry sector processes a wide array of materials, products and services with the production of chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium usually accounting for most of the sector's energy consumption in many countries. Approximately three quarters of industrial energy is used to create materials from ores, oil or biomass, with the remaining quarter used in the downstream manufacturing and construction sectors that convert materials to products. In 2010, the industry sector contributed to GHG emissions by direct combustion of carbon-based fuels (5.27 $GtCO_2$) and indirectly through purchasing electricity and steam (5.25 $GtCO_2$), as well as by chemical reactions in industrial processes (2.59 $GtCO_2$). In 2008, 42% of industrial energy supply was derived from coal and oil, 20% from gas, and the remainder from electricity and direct use of renewable energy sources (180) with coal mining and combustion having the highest number of fatalities and negative impacts on health and the environment, respectively (see Supplemental Material Section 5.10.4.1).

Despite high reductions in energy intensity in developed economies and major structural changes in developing countries during 1995–2008 (181), potential still exists for deployment of best available technologies to deliver products with low energy intensity in many countries where they are not in use. While the technical potential of energy efficiency measures in industry is estimated to be up to 25%, additional reductions of up to 20% in energy intensity may potentially be realized through innovation before approaching technological limits in some energy-intensive industries (180, 182). Up to 30% of emission reduction in industry in 2050 may result from using CCS technologies according to IEA (183). Finally, cross-country investment in mitigation technologies can enhance positive technological spillovers in host countries although this depends on additional technology policies (184–186). However, to attain stringent mitigation goals in industry options like material use efficiency, low-carbon fuel use, decarbonized electricity use, and demand reductions in other sectors (e.g., food) that lead to reduced demand for industrial products have an important role to play as well.

Besides reductions in GHG emissions technical energy efficiency measures have resulted in less fossil fuel use per ton of production and hence productivity growth at the company level (187–190) and less import of fossil fuel with less exposure to price and supply shocks (30, 38) to generate employment and income through expansion of a new appliance design sector, fiscal deficit reduction etc. (48, 191–195). Reduced fossil fuel burning leads to reduced local impacts on ecosystems through less mining activity for, e.g., coal and waste disposal liability (196, 197). There is wide consensus in the literature on local air pollution reduction benefits from energy efficiency measures in industries (193, 198, 199), such as positive health effects, and on increased safety, and improved work conditions and job satisfaction (48, 188, 200, 201).

Fuel switching options in the industry sector imply local air pollution reduction (193, 198, 199, 202) associated with health benefits (203, 204) and reduced ecosystem impacts (205). Companies individually gain from mitigation efforts through enhanced economic competitiveness, water conservation and reputation/public image building with shareholders (206). Saving on materials by enhancing efficiency in material use will enhance competitiveness (207). Industrial clusters and parks enhance resource sharing which lead to additional societal gains (208, 209), reducing the demand for virgin materials. Demand reduction for industrial products by adopting new diverse lifestyles (210–213), dietary changes (88, 214, 215) and sufficiency goals can result in multiple benefits related to climate as well as health.

The scientific literature has identified multiple benefits of many individual mitigation measures in the industry sector but the limited number of studies that have quantified such benefits in comparable metrics across studies and countries makes them difficult to include in policy implementation (e.g., CBA). Weighing and aggregating these multiple benefits that accrue to various societal stakeholders is hence difficult for national policy maker, such as for energy intensity reductions in terms of i) savings in the national import bill due to less import of coal or oil or ii) health damage cost reduction to individual households living near industrial units from reduced air pollution measured in terms of sick days reduction or valued at wage loss.

5.11 Literature cited

1. Hourcade J-C, Jaccard M, Bataille C, Ghersi F. 2006. Hybrid modeling: new answers to old challenges introduction to the special issue of the energy journal. *Energy J.* 27:1–11
2. van Vuuren D, Hoogwijk M, Barker T, Riahi K, Boeters S, et al. 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy* 37(12):5125–39
3. Edenhofer O, Kadner S, von Stechow C, Schwerhoff G, Luderer G. 2014. Linking climate change mitigation research to sustainable development. In *Handbook of Sustainable Development*, ed G Atkinson, S Dietz, E Neumayer, M Agarwala, pp. 476–99. Cheltenham, UK: Edward Elgar. 2nd Ed.
4. Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, et al. 2015. Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* 90, Part A:8–23
5. Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, et al. 2014. Assessing transformation pathways. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 413–506
6. Kriegler E, Weyant JP, Blanford GJ, Krey V, Clarke L, et al. 2014. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change* 123(3-4):353–67
7. Blanford GJ, Kriegler E, Tavoni M. 2014. Harmonization vs. fragmentation: overview of climate policy scenarios in EMF 27. *Clim. Change* 123(3-4):383–96
8. Luderer G, Bosetti V, Jakob M, Leimbach M, Steckel JC, et al. 2012. The economics of decarbonizing the energy system—results and insights from the recipe model intercomparison. *Clim. Change* 114(1):9–37
9. Luderer G, Bertram C, Calvin K, DeCian E, Kriegler E. 2016. Implications of weak near-term climate policies on long-term mitigation pathways. *Clim. Change* 136:127–140
10. Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. 2009. International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ.* 31, Supplement 2:S64–81
11. Fisher BS, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, et al. 2007. Issues related to mitigation in the long-term context. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169–250
12. Fischedick M, Schaeffer R, Adedoyin A, Akai M, Bruckner T, et al. 2011. Mitigation potential and costs. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 791–864

13. Wagner F, Amann M, Borken-Kleefeld J, Cofala J, Höglund-Isaksson L, et al. 2012. Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries. *Sustain. Sci.* 7(2):169–84
14. Greening LA, Bernow S. 2004. Design of coordinated energy and environmental policies: use of multi-criteria decision-making. *Energy Policy* 32(6):721–35
15. Munda G. 2004. Social multi-criteria evaluation: methodological foundations and operational consequences. *Eur. J. Oper. Res.* 158(3):662–77
16. Dubash NK, Raghunandan D, Sant G, Sreenivas A. 2013. Indian climate change policy. exploring a co-benefits based approach. *Econ. Polital Wkly.* 48(22):47–62
17. McCollum DL, Krey V, Riahi K, Kolp P, Grubler A, et al. 2013. Climate policies can help resolve energy security and air pollution challenges. *Clim. Change* 119(2):479–94
18. Bertram C, Johnson N, Luderer G, Riahi K, Isaac M, Eom J. 2015. Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change*. 90, Part A:62–72
19. Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, de la Vega Navarro A, et al. 2014. Energy systems. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 511–97
20. Seto KC, Dhakal S, Bigio A, Blanco H, Delgado GC, et al. 2014. Human settlements, infrastructure and spatial planning. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 923–1000
21. Doll CNH, Pachauri S. 2010. Estimating rural populations without access to electricity in developing countries through night-time light satellite imagery. *Energy Policy* 38(10):5661–70
22. Chakravarty S, Tavoni M. 2013. Energy poverty alleviation and climate change mitigation: is there a trade off? *Energy Econ.* 40, Suppl. 1:S67–73
23. Jakob M, Steckel JC, Klasen S, Lay J, Grunewald N, et al. 2014. Feasible mitigation actions in developing countries. *Nat. Clim. Change* 4(11):961–68
24. Jakob M, Steckel JC. 2014. How climate change mitigation could harm development in poor countries. *Wiley Interdiscip. Rev. Clim. Change* 5(2):161–68
25. Steckel JC, Brecha RJ, Jakob M, Strefler J, Luderer G. 2013. Development without energy?Aassessing future scenarios of energy consumption in developing countries. *Ecol. Econ.* 90:53–67
26. Krey V, Masera O, Blanford G, Bruckner T, Cooke R, et al. 2014. Annex ii: metrics & methodology. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 1281–1328

27. Blanco G, Gerlagh R, Suh S, Barrett J, de Coninck HC, et al. 2014. Drivers, trends and mitigation. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 351–411
28. Steckel JC, Edenhofer O, Jakob M. 2015. Drivers for the renaissance of coal. *PNAS* 112(29):E3775–81
29. Shrestha RM, Pradhan S. 2010. Co-benefits of CO_2 emission reduction in a developing country. *Energy Policy*. 38(5):2586–97
30. Cherp A, Adenikinju A, Goldthau A, Hernandez F, Hughes L, et al. 2012. Chapter 5 - energy and security. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 325–84. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
31. Chester L. 2010. Conceptualising energy security and making explicit its polysemic nature. *Energy Policy* 38(2):887–95
32. Sovacool BK, Brown MA. 2010. Competing dimensions of energy security: an international perspective. *Annu. Rev. Environ. Resour.* 35(1):77–108
33. Winzer C. 2012. Conceptualizing energy security. *Energy Policy* 46:36–48
34. Cherp A, Jewell J. 2014. The concept of energy security: beyond the four As. *Energy Policy* 75:415–21
35. Jewell J, Cherp A, Riahi K. 2014. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. *Energy Policy* 65:743–60
36. Yergin D. 2006. Ensuring energy security. *Foreign Aff.* 85(2):69–82
37. Cherp A, Jewell J. 2011. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. *Curr. Opin. Environ. Sustain.* 3(4):202–12
38. Cherp A, Jewell J, Vinichenko V, Bauer N, DeCian E. 2016. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Clim. Change* 136:83–94
39. Criqui P, Mima S. 2012. European climate–energy security nexus. a model based scenario analysis. *Energy Policy* 41:827–42
40. Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. 2009. Indicators for energy security. *Energy Policy* 37(6):2166–81
41. Shukla PR, Dhar S. 2011. Climate agreements and India: aligning options and opportunities on a new track. *Int. Environ. Agreem. Polit. Law Econ.* 11(3):229–43
42. Jewell J, Cherp A, Vinichenko V, Bauer N, Kober T, et al. 2013. Energy security of China, India, the EU and the U.S. under long-term scenarios: results from six IAMs. *Clim. Change Econ.* 4(4):1340011
43. Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, et al. 2012. Chapter 17 - energy pathways for sustainable development. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 1203–1306. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
44. Cai W, Wang C, Chen J, Wang S. 2011. Green economy and green jobs: myth or reality? the case of China's power generation sector. *Energy*. 36(10):5994–6003

45. Lehr U, Lutz C, Edler D. 2012. Green jobs? Economic impacts of renewable energy in Germany. *Energy Policy* 47:358–64
46. Ruiz Romero S, Colmenar Santos A, Castro Gil MA. 2012. EU plans for renewable energy. an application to the Spanish case. *Renew. Energy* 43:322–30
47. Fankhauser S, Sehlleier F, Stern N. 2008. Climate change, innovation and jobs. *Clim. Policy* 8(4):421–29
48. Wei M, Patadia S, Kammen DM. 2010. Putting renewables and energy efficiency to work: how many jobs can the clean energy industry generate in the US? *Energy Policy*. 38(2):919–31
49. Frondel M, Ritter N, Schmidt CM, Vance C. 2010. Economic impacts from the promotion of renewable energy technologies: the German experience. *Energy Policy* 38(8):4048–56
50. Böhringer C, Keller A, van der Werf E. 2013. Are green hopes too rosy? Employment and welfare impacts of renewable energy promotion. *Energy Econ.* 36:277–85
51. IEA. 2012. World energy outlook 2012. Organisation for Economic Co-operation and Development/International Energy Agency (IEA), Paris, France
52. Pachauri S, van Ruijven BJ, Nagai Y, Riahi K, van Vuuren DP, et al. 2013. Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* 8(2):024015
53. Goldemberg J, Coelho ST, Guardabassi P. 2008. The sustainability of ethanol production from sugarcane. *Energy Policy* 36(6):2086–97
54. Walter A, Dolzan P, Quilodrán O, de Oliveira JG, da Silva C, et al. 2011. Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. *Energy Policy* 39(10):5703–16
55. Bazilian M, Nussbaumer P, Eibs-Singer C, Brew-Hammond A, Modi V, et al. 2012. Improving access to modern energy services: insights from case studies. *Electr. J.* 25(1):93–114
56. Kanagawa M, Nakata T. 2007. Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. *Ecol. Econ.* 62(2):319–29
57. Sokona Y, Mulugetta Y, Gujba H. 2012. Widening energy access in Africa: towards energy transition. *Energy Policy* 47, Supplement 1:3–10
58. Casillas CE, Kammen DM. 2010. The energy-poverty-climate nexus. *Renew. Energy* 300:200
59. Rao S, Pachauri S, Dentener F, Kinney P, Klimont Z, et al. 2013. Better air for better health: forging synergies in policies for energy access, climate change and air pollution. *Glob. Environ. Change* 23(5):1122–30
60. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010. *The Lancet* 380(9859):2224–60
61. Hertwich EG. 2010. *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials*. UNEP/Earthprint. 40 pp.
62. Van Grinsven HJM, Holland M, Jacobsen BH, Klimont Z, Sutton MA, Jaap Willems W. 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. *Environ. Sci. Technol.* 47(8):3571–79
63. Burgherr P, Eckle P, Hirschberg S. 2012. Comparative assessment of severe accident risks in the coal, oil and natural gas chains. *Reliab. Eng. Syst. Saf.* 105:97–103
64. Smith KR, Frumkin H, Balakrishnan K, Butler CD, Chafe ZA, et al. 2013. Energy and human health. *Annu. Rev. Public Health* 34(1):159–88

65. Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, et al. 2014. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *PNAS* 201312753
66. Heinävaara S, Toikkanen S, Pasanen K, Verkasalo PK, Kurttio P, Auvinen A. 2010. Cancer incidence in the vicinity of Finnish nuclear power plants: an emphasis on childhood leukemia. *Cancer Causes Control*. 21(4):587–95
67. Kaatsch P, Spix C, Schulze-Rath R, Schmiedel S, Blettner M. 2008. Leukaemia in young children living in the vicinity of German nuclear power plants. *Int. J. Cancer* 122(4):721–26
68. Sermage-Faure C, Laurier D, Goujon-Bellec S, Chartier M, Guyot-Goubin A, et al. 2012. Childhood leukemia around French nuclear power plants—the Geocap study, 2002–2007. *Int. J. Cancer* 131(5):E769–80
69. van Zelm R, Huijbregts MAJ, den Hollander HA, van Jaarsveld HA, Sauter FJ, et al. 2008. European characterization factors for human health damage of PM_{10} and ozone in life cycle impact assessment. *Atmos. Environ.* 42(3):441–53
70. Jack DW, Kinney PL. 2010. Health co-benefits of climate mitigation in urban areas. *Curr. Opin. Environ. Sustain.* 2(3):172–77
71. Bell ML, Davis DL, Cifuentes LA, Krupnick AJ, Morgenstern RD, Thurston GD. 2008. Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environ. Health* 7:41
72. Hertwich EG, Hammitt JK. 2001. A decision-analytic framework for impact assessment part i: LCA and decision analysis. *Int. J. Life Cycle Assess.* 6(1):5–12
73. Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, et al. 2011. Renewable energy in the context of sustainable development. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 707–789
74. Corsten M, Ramírez A, Shen L, Koornneef J, Faaij A. 2013. Environmental impact assessment of CCS chains–lessons learned and limitations from LCA literature. *Int. J. Greenh. Gas Control* 13:59–71
75. Schakel W, Meerman H, Talaei A, Ramírez A, Faaij A. 2014. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. *Appl. Energy* 131:441–67
76. Giavi S, Moretti M, Bontadina F, Zambelli N, Schaub M. 2014. Seasonal survival probabilities suggest low migration mortality in migrating bats. *PLoS ONE* 9(1):E85628
77. Lehnert LS, Kramer-Schadt S, Schönborn S, Lindecke O, Niermann I, Voigt CC. 2014. Wind farm facilities in Germany kill noctule bats from near and far. *PLoS ONE* 9(8):E103106
78. Marques AT, Batalha H, Rodrigues S, Costa H, Pereira MJR, et al. 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. *Biol. Conserv.* 179:40–52
79. Bellebaum J, Korner-Nievergelt F, Dürr T, Mammen U. 2013. Wind turbine fatalities approach a level of concern in a raptor population. *J. Nat. Conserv.* 21(6):394–400
80. Sovacool BK. 2013. The avian benefits of wind energy: a 2009 update. *Renew. Energy* 49:19–24
81. Kibler KM, Tullos DD. 2013. Cumulative biophysical impact of small and large hydropower development in Nu River, China. *Water Resour. Res.* 49(6):3104–18

82. Piman T, Lennaerts T, Southalack P. 2013. Assessment of hydrological changes in the lower Mekong basin from basin-wide development scenarios. *Hydrol. Process* 27(15):2115–25
83. Ziv G, Baran E, Nam S, Rodríguez-Iturbe I, Levin SA. 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River basin. *PNAS* 109(15):5609–14
84. Meldrum J, Nettles-Anderson S, Heath G, Macknick J. 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environ. Res. Lett.* 8(1):015031
85. Verones F, Hanafiah MM, Pfister S, Huijbregts MAJ, Pelletier GJ, Koehler A. 2010. Characterization factors for thermal pollution in freshwater aquatic environments. *Environ. Sci. Technol.* 44(24):9364–69
86. Zhai H, Rubin ES, Versteeg PL. 2011. Water use at pulverized coal power plants with postcombustion carbon capture and storage. *Environ. Sci. Technol.* 45(6):2479–85
87. Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, et al. 2011. Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 209-331
88. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, et al. 2014. Agriculture, forestry and other land use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 811–922
89. Bustamante M, Robledo-Abad C, Harper R, Mbow C, Ravindranat NH, et al. 2014. Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Glob. Change Biol.* 20(10):3270–90
90. Creutzig F, Corbera E, Bolwig S, Hunsberger C. 2013. Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environ. Res. Lett.* 8(3):035047
91. Popp A, Dietrich JP, Lotze-Campen H, Klein D, Bauer N, et al. 2011. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ. Res. Lett.* 6(3):034017
92. Dauvergne P, Neville KJ. 2010. Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *J. Peasant Stud.* 37(4):631–60
93. van der Horst D, Vermeylen S. 2011. Spatial scale and social impacts of biofuel production. *Biomass Bioenergy* 35(6):2435–43
94. Wilkinson J, Herrera S. 2010. Biofuels in Brazil: debates and impacts. *J. Peasant Stud.* 37(4):749–68
95. Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, et al. 2015. Bioenergy and climate change mitigation: an assessment. *Glob Chance Biol Bioenergy* 7(5): 916–944
96. Robledo-Abad C, Althaus HJ, Berndes G, Bolwig S, Corbera E, et al. 2017. Bioenergy production and sustainable development: science base for policymaking remains limited. *Glob Chance Biol Bioenergy* 9(3): 541–556

97. Smith P, Haberl H, Popp A, Erb K, Lauk C, et al. 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* 19(8):2285–2302
98. Finco MVA, Doppler W. 2010. Bioenergy and sustainable development: the dilemma of food security and climate change in the Brazilian savannah. *Energy Sustain. Dev.* 14(3):194–99
99. Amigun B, Musango JK, Stafford W. 2011. Biofuels and sustainability in Africa. *Renew. Sustain. Energy Rev.* 15(2):1360–72
100. Huang J, Yang J, Msangi S, Rozelle S, Weersink A. 2012. Biofuels and the poor: global impact pathways of biofuels on agricultural markets. *Food Policy* 37(4):439–51
101. Duvenage I, Taplin R, Stringer LC. 2012. Towards implementation and achievement of sustainable biofuel development in Africa. *Environ. Dev. Sustain.* 14(6):993–1012
102. Arndt C, Pauw K, Thurlow J. 2012. Biofuels and economic development: a computable general equilibrium analysis for Tanzania. *Energy Econ.* 34(6):1922–30
103. Haberl H, Mbow C, Deng X, Irwin EG, Kerr S, et al. 2014. Finite land resources and competition. *Rethink. Glob. Land Use Urban Era MIT Press Camb.*
104. Borzoni M. 2011. Multi-scale integrated assessment of soybean biodiesel in Brazil. *Ecol. Econ.* 70(11):2028–38
105. Ewing M, Msangi S. 2009. Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environ. Sci. Policy* 12(4):520–28
106. German L, Schoneveld GC, Gumbo D. 2011. The local social and environmental impacts of smallholder-based biofuel investments in Zambia. *Ecol. Soc.* 16(4):12
107. German L, Schoneveld G. 2012. A review of social sustainability considerations among EU-approved voluntary schemes for biofuels, with implications for rural livelihoods. *Energy Policy* 51:765–78
108. Hall J, Matos S, Severino L, Beltrão N. 2009. Brazilian biofuels and social exclusion: established and concentrated ethanol versus emerging and dispersed biodiesel. *J. Clean. Prod.* 17:S77–85
109. IPCC. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]*. Cambridge University Press, Cambridge, UK, and New York, NY, USA
110. Koh LP, Ghazoul J. 2008. Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities. *Biol. Conserv.* 141(10):2450–60
111. Sala OE, Chapin FS, III, Armesto JJ, Berlow E, et al. 2000. Global biodiversity scenarios for the year 2100. *Science* 287(5459):1770–74
112. Thompson MC, Baruah M, Carr ER. 2011. Seeing REDD+ as a project of environmental governance. *Environ. Sci. Policy* 14(2):100–110
113. Tilman D, Socolow R, Foley JA, Hill J, Larson E, et al. 2009. Beneficial biofuels—the food, energy, and environment trilemma. *Science* 325(5938):270
114. Baka J. 2013. The political construction of wasteland: governmentality, land acquisition and social inequality in south India. *Dev. Change* 44(2):409–28
115. Herrmann IT, Jørgensen A, Bruun S, Hauschild MZ. 2013. Potential for optimized production and use of rapeseed biodiesel. Based on a comprehensive real-time LCA case study in Denmark with multiple pathways. *Int. J. Life Cycle Assess.* 18(2):418–30

116. Liang S, Xu M, Zhang T. 2012. Unintended consequences of bioethanol feedstock choice in China. *Bioresour. Technol.* 125:312–17
117. Mwakaje AG. 2012. Can Tanzania realise rural development through biofuel plantations? insights from the study in Rufiji district. *Energy Sustain. Dev.* 16(3):320–27
118. Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, et al. 2009. Implications of limiting CO_2 concentrations for land use and energy. *Science* 324(5931):1183–86
119. Hunsberger C, Bolwig S, Corbera E, Creutzig F. 2014. Livelihood impacts of biofuel crop production: implications for governance. *Geoforum*. 54:248–60
120. Franco J, Levidow L, Fig D, Goldfarb L, Hönicke M, Mendonca L. 2010. Assumptions in the European union biofuels policy: frictions with experiences in Germany, Brazil and Mozambique. *J. Peasant Stud.* 37(4):661–98
121. Partzsch L. 2009. The legitimacy of biofuel certification. *Agric. Hum. Values* 28(3):413–25
122. Creutzig F, Popp A, Plevin RJ, Luderer G, Minx J, Edenhofer O. 2012. Reconciling top-down and bottom-up modeling on future bioenergy deployment. *Nat. Clim. Change* 2:320–27
123. Creutzig F, von Stechow C, Klein D, Hunsberger C, Bauer N, et al. 2012. Can bioenergy assessments deliver? *Econ. Energy Environ. Policy* 1(2):65–82
124. Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, et al. 2014. Transport. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 599–670
125. Costantini V, Gracceva F, Markandya A, Vicini G. 2007. Security of energy supply: comparing scenarios from a European perspective. *Energy Policy*. 35(1):210–26
126. Sorrell S, Speirs J, Bentley R, Brandt A, Miller R. 2010. Global oil depletion: a review of the evidence. *Energy Policy* 38(9):5290–95
127. Leiby PN. 2007. *Estimating the Energy Security Benefits of Reduced US Oil Imports*. Oak Ridge, TN: Oak Ridge National Laboratory
128. Shakya SR, Shrestha RM. 2011. Transport sector electrification in a hydropower resource rich developing country: energy security, environmental and climate change co-benefits. *Energy Sustain. Dev.* 15(2):147–59
129. Creutzig F, Mühlhoff R, Römer J. 2012. Decarbonizing urban transport in European cities: four cases show possibly high co-benefits. *Environ. Res. Lett.* 7(4):044042
130. Leung GC. 2011. China's energy security: perception and reality. *Energy Policy* 39(3):1330–37
131. Banister D. 2008. The sustainable mobility paradigm. *Transp. Policy*. 15(2):73–80
132. Miranda H de F, Rodrigues da Silva AN. 2012. Benchmarking sustainable urban mobility: the case of Curitiba, Brazil. *Transp. Policy* 21:141–51
133. Boschmann EE. 2011. Job access, location decision, and the working poor: a qualitative study in the Columbus, Ohio metropolitan area. *Geoforum*. 42(6):671–82
134. Sietchiping R, Permezel MJ, Ngomsi C. 2012. Transport and mobility in sub-Saharan African cities: an overview of practices, lessons and options for improvements. *Cities* 29(3):183–89
135. Banister D. 2011. Cities, mobility and climate change. *J. Transp. Geogr.* 19(6):1538–46

136. Goodwin P. 2004. The economic costs of road traffic congestion. UCL (University College London), The Rail Freight Group, London, UK
137. Creutzig F, He D. 2009. Climate change mitigation and co-benefits of feasible transport demand policies in Beijing. *Transp. Res. Part Transp. Environ.* 14(2):120–31
138. World Bank. 2002. Cities on the move: a World Bank urban transport strategy review. The World Bank, Washington, D.C.
139. JICA. 2005. The master plan for Lima and Callao metropolitan area urban transportation in the Republic of Peru; chapter 6, traffic control and management conditions. Transport Council of Lima and Callao, Ministry of Transportation and Communications of the Republic of Peru and Japan International Cooperation Agency (JICA)
140. Kunieda M, Gauthier A. 2007. Sustainable transport: a sourcebook for policy-makers in developing cities. Module 7a: gender and urban transport: smart and affordable. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany
141. Figueroa M, Lah O, Fulton LM, McKinnon A, Tiwari G. 2014. Energy for transport. *Annu. Rev. Environ. Resour.* 39(1):295–325
142. Lah O, Sohr A, Bei X, Glensor K, Hüging H, Müller M. 2014. Metrasys, sustainable mobility for megacities: traffic management and low-carbon transport for Hefei, China. In *Future Megacities 2 - Mobility and transportation concepts for sustainable transportation in future megacities*, ed W-H Arndt, pp. 94–106. Berlin, Germany: Jovis Verlag
143. WHO. 2013. Who global status report on road safety 2013: supporting a decade of action. World Health Organization (WHO), Geneva, Switzerland
144. De Hartog JJ, Boogaard H, Nijland H, Hoek G. 2010. Do the health benefits of cycling outweigh the risks? *Environ. Health Perspect.* 118(8):1109–16
145. Rabl A, De Nazelle A. 2012. Benefits of shift from car to active transport. *Transp. Policy* 19(1):121–31
146. Rojas-Rueda D, de Nazelle A, Tainio M, Nieuwenhuijsen MJ. 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. *BMJ* 343:d4521
147. Tiwari G, Jain D. 2012. Accessibility and safety indicators for all road users: case study Delhi BRT. *J. Transp. Geogr.* 22:87–95
148. Sonkin B, Edwards P, Roberts I, Green J. 2006. Walking, cycling and transport safety: an analysis of child road deaths. *J. R. Soc. Med.* 99(8):402–5
149. Kahn Ribeiro S, Figueroa MJ, Creutzig F, Dubeux C, Hupe J, Kobayashi S. 2012. Chapter 9 - energy end-use: transport. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 575–648. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
150. Hill J, Polasky S, Nelson E, Tilman D, Huo H, et al. 2009. Climate change and health costs of air emissions from biofuels and gasoline. *PNAS* 106(6):2077–82
151. Smith KR, Balakrishnan K, Butler C, Chafe Z, Fairlie I, et al. 2012. Chapter 4 - energy and health. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 255–324. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
152. Woodcock J, Edwards P, Tonne C, Armstrong BG, Ashiru O, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*. 374(9705):1930–43

153. Ürge-Vorsatz D, Eyre N, Graham P, Harvey D, Hertwich E, et al. 2012. Chapter 10 - energy end-use: building. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 649–760. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
154. Pachauri S, Brew-Hammond A, Barnes DF, Bouille DH, Gitonga S, et al. 2012. Chapter 19 - energy access for development. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 1401–58. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
155. Zhang J (Jim), Smith KR. 2007. Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions. *Environ. Health Perspect.* 115(6):848–55
156. Wilkinson P, Smith KR, Davies M, Adair H, Armstrong BG, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet* 374(9705):1917–29
157. Pope DP, Mishra V, Thompson L, Siddiqui AR, Rehfuess EA, et al. 2010. Risk of low birth weight and stillbirth associated with indoor air pollution from solid fuel use in developing countries. *Epidemiol. Rev.*, p. mxq005
158. Kunreuther H, Gupta S, Bosetti V, Cooke R, Dutt V, et al. 2014. Integrated risk and uncertainty assessment of climate change response policies. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 151–205
159. Singh A, Syal M, Grady SC, Korkmaz S. 2010. Effects of green buildings on employee health and productivity. *Am. J. Public Health* 100(9):1665–68
160. Clinch JP, Healy JD. 2001. Cost-benefit analysis of domestic energy efficiency. *Energy Policy* 29(2):113–24
161. Marmot Review Team. 2011. The health impacts of cold homes and fuel poverty. Friends of the Earth and the Marmot Review Team, London, UK
162. Smith KR, Jerrett M, Anderson HR, Burnett RT, Stone V, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *The Lancet* 374(9707):2091–2103
163. Harlan SL, Ruddell DM. 2011. Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Curr. Opin. Environ. Sustain.* 3(3):126–34
164. Emberson L, He K, Rockström J, Amann M, Barron J, et al. 2012. Chapter 3 - energy and environment. In *Global Energy Assessment - Toward a Sustainable Future*, pp. 191–254. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria
165. Levy JI, Nishioka Y, Spengler JD. 2003. Environmental health: a global access science source. *Environ. Health Glob. Access Sci. Source*. 2:4
166. Naess-Schmidt HS, Hansen MB, von Utfall Danielsson C. 2012. Multiple benefits of investing in energy efficient renovation of buildings, commissioned by renovate Europe. Copenhagen Economics, Copenhagen, Denmark
167. Ürge-Vorsatz D, Tirado Herrero S. 2012. Building synergies between climate change mitigation and energy poverty alleviation. *Energy Policy* 49:83–90

168. Bruce N, Rehfuess EA, Mehta S, Hutton G, Smith KR. 2006. Indoor air pollution. In *Disease control priorities in developing countries*, ed DT Jamison, JG Breman, AR Measham, G Alleyne, M Claeson, et al., pp. 793–815. Washington, DC: World Bank
169. Fisk WJ. 2002. How IEQ affects health, productivity. *ASHRAE J.* 44(5):56–56
170. Milner J, Davies M, Wilkinson P. 2012. Urban energy, carbon management (low carbon cities) and co-benefits for human health. *Curr. Opin. Environ. Sustain.* 4(4):398–404
171. Scott MJ, Roop JM, Schultz RW, Anderson DM, Cort KA. 2008. The impact of DOE building technology energy efficiency programs on U.S. employment, income, and investment. *Energy Econ.* 30(5):2283–2301
172. Pollin R, Heintz J, Garrett-Peltier H. 2009. The economic benefits of investing in clean energy: how the economic stimulus program and new legislation can boost U.S. economic growth and employment. Political Economy Research Institute, University of Massachusetts at Amherst
173. ILO, UNEP. 2012. Working towards sustainable development: opportunities for decent work and social inclusion in a green economy. International Labour Organization (ILO) and United Nations Environment Programme (UNEP), Geneva, Switzerland
174. Carley S, Lawrence S, Brown A, Nourafshan A, Benami E. 2011. Energy-based economic development. *Renew. Sustain. Energy Rev.* 15(1):282–95
175. Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, et al. 2014. Buildings. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 671–738
176. Bartik TJ. 2012. Including jobs in benefit-cost analysis. *Annu. Rev. Resour. Econ.* 4(1):55–73
177. Mirasgedis S, Tourkolias C, Pavlakis E, Diakoulaki D. 2014. A methodological framework for assessing the employment effects associated with energy efficiency interventions in buildings. *Energy Build.* 82:275–86
178. Loftness V, Hartkopf V, Gurtekin B, Hansen D, Hitchcock R. 2003. Linking energy to health and productivity in the built environment. Center for Building Performance and Diagnostics, Carnegie Mellon University, Pittsburgh, PA
179. Ürge-Vorsatz D, Tirado Herrero S, Dubash NK, Lecocq F. 2014. Measuring the co-benefits of climate change mitigation. *Annu. Rev. Environ. Resour.* 39(1):549–82
180. Fischedick M, Roy J, Abdel-Aziz A, Acquaye A, Allwood JM, et al. 2014. Industry. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, pp. 739–810
181. UNIDO. 2011. Industrial development report 2011. Industrial energy efficiency for sustainable wealth creation: capturing environmental, economic and social dividends. United Nations Industrial Development Organization (UNIDO), Vienna, Austria

182. Allwood JM, Cullen JM, Milford RL. 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environ. Sci. Technol.* 44(6):1888–94
183. IEA. 2009. Energy technology transitions for industry. Strategies for the next industrial revolution. Organisation for Economic Co-operation and Development/International Energy Agency (IEA), Paris, France
184. Jeon Y, Park BI, Ghauri PN. 2013. Foreign direct investment spillover effects in China: are they different across industries with different technological levels? *China Econ. Rev.* 26:105–17
185. Costantini V, Mazzanti M, Montini A. 2013. Environmental performance, innovation and spillovers. Evidence from a regional NAMEA. *Ecol. Econ.* 89:101–14
186. Wang C, Deng Z, Kafouros MI, Chen Y. 2012. Reconceptualizing the spillover effects of foreign direct investment: a process-dependent approach. *Int. Bus. Rev.* 21(3):452–64
187. Boyd GA, Pang JX. 2000. Estimating the linkage between energy efficiency and productivity. *Energy Policy* 28(5):289–96
188. Worrell E, Laitner JA, Ruth M, Finman H. 2003. Productivity benefits of industrial energy efficiency measures. *Energy* 28(11):1081–98
189. Zhang J, Wang G. 2008. Energy saving technologies and productive efficiency in the Chinese iron and steel sector. *Energy*. 33(4):525–37
190. May G, Taisch M, Stahl B, Sadr V. 2012. Toward energy efficient manufacturing: a study on practices and viewpoint of the industry. In *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*, ed C Emmanouilidis, M Taisch, D Kiritsis, pp. 1–8. Berlin/Heidelberg, Germany: Springer
191. IEA. 2012. Spreading the net: the multiple benefits of energy efficiency improvements. Organisation for Economic Co-operation and Development/International Energy Agency (IEA), Paris, France
192. Roy J, Dasgupta S, Chakravarty D. 2013. Energy efficiency: technology, behavior, and development. In *The Handbook of Global Energy Policy*, ed A Goldthau, pp. 282–302. New York: John Wiley & Sons Ltd
193. Winkler H, Howells M, Baumert K. 2007. Sustainable development policies and measures: institutional issues and electrical efficiency in South Africa. *Clim. Policy* 7(3):212–29
194. Horbach J, Rennings K. 2013. Environmental innovation and employment dynamics in different technology fields – an analysis based on the German community innovation survey 2009. *J. Clean. Prod.* 57:158–65
195. Sathaye J. 2010. Eliminating electricity deficit through energy efficiency in India: an evaluation of aggregate economic and carbon benefits. Lawrence Berkeley National Laboratory, Berkeley, CA
196. Hasanbeigi A, Lobscheid A, Lu H, Price L, Dai Y. 2013. Quantifying the co-benefits of energy-efficiency policies: a case study of the cement industry in Shandong province, China. *Sci. Total Environ.* 458–460:624–36
197. Lee T, van de Meene S. 2013. Comparative studies of urban climate co-benefits in Asian cities: an analysis of relationships between CO_2 emissions and environmental indicators. *J. Clean. Prod.* 58:15–24
198. Ren W, Geng Y, Xue B, Fujita T, Ma Z, Jiang P. 2012. Pursuing co-benefits in China's old industrial base: a case of Shenyang. *Urban Clim.* 1:55–64
199. Bassi AM, Yudken JS, Ruth M. 2009. Climate policy impacts on the competitiveness of energy-intensive manufacturing sectors. *Energy Policy* 37(8):3052–60
200. Getzner M. 2002. The quantitative and qualitative impacts of clean technologies on employment. *J. Clean. Prod.* 10(4):305–19

201. Zhang D, Aunan K, Martin Seip H, Vennemo H. 2011. The energy intensity target in China's 11th five-year plan period—local implementation and achievements in Shanxi province. *Energy Policy* 39(7):4115–24
202. Kuramochi T, Ramírez A, Turkenburg W, Faaij A. 2012. Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes. *Prog. Energy Combust. Sci.* 38(1):87–112
203. Aunan K, Fang J, Vennemo H, Oye K, Seip HM. 2004. Co-benefits of climate policy – lessons learned from a study in Shanxi, China. *Energy Policy* 32(4):567–81
204. Haines A, McMichael AJ, Smith KR, Roberts I, Woodcock J, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *The Lancet* 374(9707):2104–14
205. Mestl HE, Aunan K, Fang J, Seip HM, Skjelvik JM, Vennemo H. 2005. Cleaner production as climate investment—integrated assessment in Taiyuan city, China. *J. Clean. Prod.* 13(1):57–70
206. Chakraborty D, Roy J. 2012. Accounting for corporate water use: estimating water footprint of an Indian paper production unit. *J Indian Acc. Rev*. 16(2):34–42
207. Meyer B, Distelkamp M, Wolter MI. 2007. Material efficiency and economic-environmental sustainability. Results of simulations for Germany with the model Panta Rhei. *Ecol. Econ.* 63(1):192–200
208. Lowe EA. 1997. Creating by-product resource exchanges: strategies for eco-industrial parks. *J. Clean. Prod.* 5(1–2):57–65
209. Chertow MR. 2000. Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25(1):313–37
210. Allwood JM, Ashby MF, Gutowski TG, Worrell E. 2013. Material efficiency: providing material services with less material production. *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* 371(1986):20120496
211. Kainuma M, Shukla PR, Jiang K. 2012. Framing and modeling of a low carbon society: an overview. *Energy Econ.* 34, Supplement 3:S316–24
212. Roy J, Pal S. 2009. Lifestyles and climate change: link awaiting activation. *Curr. Opin. Environ. Sustain.* 1(2):192–200
213. GEA. 2012. *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. 1865 pp.
214. Popp A, Lotze-Campen H, Bodirsky B. 2010. Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Glob. Environ. Change* 20(3):451–62
215. Stehfest E, Bouwman L, van Vuuren DP, den Elzen MG, Eickhout B, Kabat P. 2009. Climate benefits of changing diet. *Clim. Change* 95(1-2):83–102

6 2°C and SDGs: United they stand, divided they fall?

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Keywords

Climate change mitigation, climate policy, co-benefits, risk management, energy efficiency, sustainable development, mitigation risks

Abstract

The adoption of the Sustainable Development Goals (SDGs) and the new international climate treaty could put 2015 into the history books as a defining year for setting human development on a more sustainable pathway. The global climate policy and SDG agendas are highly interconnected: the way that the climate problem is addressed strongly affects the prospects of meeting numerous other SDGs and vice versa. Drawing on existing scenario results from a recent energy-economy-climate model inter-comparison project, this letter analyzes these synergies and (risk) trade-offs of alternative 2°C pathways across indicators relevant for energy-related SDGs and sustainable energy objectives. We find that limiting the availability of key mitigation technologies yields some co-benefits and decreases risks specific to these technologies but greatly increases many others. Fewer synergies and substantial trade-offs across SDGs are locked into the system for weak short-term climate policies that are broadly in line with current Intended Nationally Determined Contributions (INDCs), particularly when combined with constraints on technologies. Lowering energy demand growth is key to managing these trade-offs and creating synergies across multiple energy-related SD dimensions. We argue that SD considerations are central for choosing socially acceptable 2°C pathways: the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Progress on the climate policy and SDG agendas should therefore be tracked within a unified framework.

6.1 Introduction

There is hope that 2015 will be remembered as a defining year for setting human development on a more sustainable pathway. Two important milestones were reached. On 25 September, a new development agenda was adopted in New York aimed at eradicating poverty and facilitating inclusive development within ever tighter planetary boundaries. Economic, social and environmental progress will be tracked across a set of agreed sustainable development goals (SDGs). The SDG framework is intended to manage trade-offs and maximize synergies across the 17 different goals and associated 169 targets (Griggs et al 2013).

On 12 December, countries agreed upon a new international climate treaty, the Paris Agreement, at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris. It 'aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by holding the increase in the global average temperature to well below 2°C above preindustrial levels' (UNFCCC2015a).

Both processes are highly interrelated: SD is an explicit part of the Paris Agreement, while avoiding dangerous climate change features as one of the SDGs (#13). In fact, failure in one process would undermine the success of the other. Stringent and sustained mitigation is a necessary condition for SD, because unabated climate change will exacerbate many of today's development issues and negate future improvements (see Fleurbaey et al 2014). However, it is an insufficient condition for SD, because some 2°C pathways could, if not designed properly, undermine SD in non-climate dimensions. For example, pathways with a limited short-term ambition like the current INDCs may have higher SD risks than more ambitious ones. Such broader SD implications could delegitimize some 2°C pathways or even the 2°C target itself (Edenhofer and Kowarsch 2015). SD further hinges on the successful implementation of non-climate policies that complement or support climate policies in other dimensions. Thus, identifying socially acceptable 2°C pathways requires framing climate policy in a broader SD context.

Assessments of alternative mitigation pathways so far have mainly focused on characterizing the underlying technological and economic challenges (Clarke et al 2014), but less is known about the wider social, economic and environmental implications. For example, many 2°C pathways project large amounts of bioenergy demand in the second half of this century. It is highly debated in the literature whether these can be provided sustainably: food security, place-specific livelihoods, water availability and biodiversity are amongst the critical issues being discussed (Creutzig et al 2012, Smith et al 2014). At the same time, many 2°C pathways project potential health gains and co-benefits for other sustainability objectives. The balance of these co-effects is poorly understood, particularly on the supply side, because risks of alternative 2°C pathways for non-climate sustainability objectives have not yet been systematically analyzed (von Stechow et al 2015).

In this letter, we analyze the implications of alternative 2°C pathways for SD risk dimensions by drawing on existing, publicly available inter-model comparison results from integrated energy-economy climate models—henceforth referred to as integrated models (see SI section, available at stacks.iop.org/ERL/11/034022/mmedia and in section 6.8). We demonstrate how broadening the analytical framework can allow both for a more informed public debate about alternative 2°C pathways and how achieving the climate SDG may affect the prospects of meeting other energy-related SDGs. This is important both for critically discussing the relationship between the international climate policy and SDG agendas as well as for identifying stringent mitigation pathways that are socially acceptable.

6.2 Methods

Choosing appropriate climate policies is an exercise in risk management for which it is key to understand and evaluate relevant uncertainties (Kunreuther et al 2013). We focus on uncertainties related to different model structures and assumptions, i.e. 'model uncertainty' (Drouet et al 2015) and draw on results from a structured inter-comparison exercise of integrated energy-economy-climate models, AMPERE (Kriegler et al 2015, Riahi et al 2015). To complement existing literature, this data is used to assess relevant SD implications of alternative clusters of mitigation pathways that are consistent with the 2°C target (see Table S-6.2) to initiate a public debate on their wider sustainability implications.

6.2.1 Choice of indicators for SD risks

The analysis builds on recent literature that explores a growing number of mitigation challenges with implications for non-climate sustainability objectives. Comprehensive discussions can be found in Clarke et al (2014, section 6.6) and von Stechow et al (2015, section 4). Table 6.1 summarizes the indicators that can be calculated from integrated model variables. Our choice of indicators is further constrained by the model structures, scenario runs, and reported variables as aggregated in the publicly available AMPERE database (https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB). For example, the coarse regional disaggregation of reported data in AMPERE impedes the analysis of indicators that are most relevant for inequality and poverty outcomes, such as energy supply per capita to satiate basic human needs (see Steckel et al 2013, Lamb and Rao 2015 and SI section 6.8.2 for a discussion of further model limitations). By systematically linking the chosen set of indicators to global SD risks, we can present a first, rough approximation of how alternative clusters of 2°C pathways perform with respect to energy-related SDGs and other multilaterally agreed sustainable energy objectives (see Table 6.2 and SI section 6.8.3 for a discussion on the indicator choice).

Due to the limited data availability, the analysis cannot address all relevant SDGs explicitly. But it enables us to provide an early contribution to public and scientific debates on the relationship between the international climate policy and SDG agendas and contribute to important early learning processes. To simplify the complex relationship between indicators, energy-related SDGs and other sustainable energy objectives (see Figure S-6.2), Table 6.2 focuses on the strongest links between them.

Table 6.1 Integrated model literature on mitigation challenges with implications for non-climate sustainability objectives, with a focus on indicators that can be calculated from model variables. The different categories largely follow Table 4.1 in Fleurbaey et al (2014). Due to strengths and weaknesses of the models, some mitigation challenges were only analyzed by individual models while others were covered by multiple models—mostly in the context of model inter-comparison projects. A comprehensive review on co-benefits and risks of mitigation is provided in von Stechow et al (2015).

Mitigation challenges	Indicators used	Selected literature
Economic/affordability challenges		
Aggregate economic costs of mitigation	Aggregated and discounted GDP/consumption losses	Kriegler et al 2013, Paltsev and Capros 2013, Clarke et al 2014, Kriegler et al 2014, Rogelj et al 2015
Transitional economic costs of mitigation	Consumption growth reduction	Kriegler et al 2013, Luderer et al 2013, 2016, Bertram et al 2015b
Carbon price growth	Carbon price jump over a decade Global energy price index	Rogelj et al 2013a, 2015 Luderer et al 2013, Bertram et al 2015b
Energy price growth	Electricity price growth rate	Kriegler et al 2013, Rogelj et al 2015
Stranded fossil investment	Idle power plant capacity per year	Luderer et al 2013, Rogelj et al 2013a, Bertram et al 2015a, Johnson et al 2015
Energy dependence	Trade flows between regions	Cherp et al 2016, Jewell et al 2013, 2014, Riahi et al 2012
Resilience of energy systems	Diversity of energy carriers in individual sectors (SWDI, HHI)	Cherp et al 2016, Jewell et al 2013, 2014
Depletion of oil reserves	Cumulative oil extraction	Sathaye et al 2011, Jewell et al 2013
Technological/innovation challenges		
Integration challenges of low-carbon technologies	Technological upscaling (rates)	Wilson et al 2013, Kim et al 2014, Eom et al 2015, Riahi et al 2015, van Sluisveld et al 2015, Bertram et al 2015a
Carbon intensity improvement	Carbon intensity reduction rates	Luderer et al 2013, Edenhofer et al 2014a, Kriegler et al 2014, Riahi et al 2015
Social/institutional challenges		
Food price increase	World and regional market prices	von Braun et al 2008, PBL 2012, Lotze-Campen et al 2014, Wise et al 2014, van Vuuren et al 2015
Energy supply per capita/ energy access	Final energy supply per year/access to modern fuels	van Ruijven et al 2012, Daioglou et al 2012, Krey et al 2012, Steckel et al 2013, Riahi et al 2012, Pachauri et al 2013, Lamb and Rao 2015, van Vuuren et al 2015
Nuclear proliferation	Enrichment/reprocessing facilities	Lehtveer and Hedenus 2015
Carbon market value	Value of cumulative emissions	Luderer et al 2013, Bertram et al 2015b
Environmental challenges		
Resource extraction/use	Cumulative coal/uranium extraction	Rogner et al 2012, Bauer et al 2013, McCollum et al 2014
Bioenergy expansion	Biomass supply for energy	Creutzig et al 2012, Smith et al 2014
Air pollutant concentration	SO_2, BC, OC and NO_x emissions/concentrations	Riahi et al 2012, McCollum et al 2013a, Rogelj et al 2014, Rose et al 2014, Strefler et al 2014, van Vuuren et al 2015
Environmental risks of CO_2 capture and storage	CO_2 (fossil/biomass) captured and stored underground	Kriegler et al 2013, Eom et al 2015, Rogelj et al 2015, Smith et al 2016
Land use change	Global area changes for cropland, pasture, biomass, unmanaged land	Wise et al 2009, Reilly et al 2012, Lotze-Campen et al 2014, Popp et al 2014, Calvin et al 2014
Water shortage	Water use (mainly for bioenergy supply)	De Fraiture et al 2008, Arnell et al 2011, PBL 2012, Hejazi et al 2013, Bonsch et al 2016
Biodiversity loss (MSA)	Mean species abundance	PBL 2012, van Vuuren et al 2015
Peak atmospheric CO_2 concentration	Cumulative CO_2 emissions until mid-century	Joos et al 2011, Zickfeld et al 2012
Exceedance likelihood/ overshoot risk	Likelihood of exceeding specific temperature/concentration target	Kriegler et al 2013, Luderer et al 2013, Rogelj et al 2013a, 2013b

However, many indicators are also relevant for some cross-cutting SDGs, such as poverty and inequality, which are not addressed in the analysis (see SI section 6.8.3.1). The resulting set of indicators is relevant for judging both co-benefits of mitigation (air quality, oil security) and mitigation risks (upscaling of bioenergy and low-carbon electricity technologies) and has been shown to have substantial sustainability implications in many integrated models (Jewell et al 2013, McCollum et al 2013a, von Stechow et al 2015). It also includes an indicator for ocean acidification (Joos et al 2011, Zickfeld et al 2012) as well as three indicators that relate to transitional socioeconomic mitigation risks (growth in mitigation costs and energy prices as well as early retirement of coal capacity).

Our analysis presents SD risk profiles for alternative clusters of 2°C pathways (see Figures 6.2–6.4). The figures plot percentage changes over baseline projections in each dimension rather than comparing different metrics to each other and/or identifying critical thresholds because of the difficulty of incommensurability across different SD dimensions (von Stechow et al 2015). Care needs to be taken in the interpretation, because the different risks analyzed cannot be directly compared to each other, i.e. a larger increase in one risk is not necessarily more important than a smaller increase in another risk. Any interpretation of these risk profiles and any trade-off across risk dimensions requires evaluation and weighting—and this depends on the locally specific policy contexts and differ depending on individual priorities and risk perceptions (Slovic 1987, Jakob and Edenhofer 2014, Kunreuther et al 2014). The provided risk profiles therefore allow readers to make their own judgement about the relevance of changes in risk levels across SD dimensions. In this sense our analysis provides a starting point for a more informed public debate about the interaction between the mitigation and other energy-related SDGs that will put the normative aspects of such evaluation centre stage (see Edenhofer et al 2014b).

Table 6.2 The link between relevant and available indicators calculated from integrated model variables, SD risk dimensions, and SDGs and other sustainable energy objectives. See Figure S-6.2 and SI section 6.8.3 for more details.

Indicators calculated from integrated model variables	SD risk dimensions affected by Mitigation	SDGs and other sustainable energy objectives
Biomass supply for energy per year	Bioenergy expansion	Food security (SDG 2)
Cumulative BC and SO2 emissions	Air pollutant concentration	Health via air quality (SDG 3.9)
Maximum decadal energy price growth	Energy price growth)	Energy access (SDG 7)
Maximum decadal growth reduction	Consumption growth reduction	Economic growth (SDG 8.1)
Idle coal capacity per year	Stranded fossil investment	Full employment (SDG 8.3)
Maximum decadal PV and Wind upscaling	Wind&PV grid integration	Resilient infrastructure (SDG 9)
Cumulative global oil trade, cumulative oil extraction, fuel diversity of transport sector	Oil insecurity, transport sector, reliance on oil	Ensure energy security[a]
Nuclear capacity expansion in Newcomers[b]	Nuclear proliferation	Peaceful use of nuclear power
Cumulative CO_2 emissions until mid-century	Peak atmospheric CO_2 concentration	Minimize ocean acidification (SDG 14.3)
CO_2 captured and stored per year	Environmental risks of CCS	Sustainable production (SDG 12.4)

[a] **Due to the focus on global risks, the analysis is limited to oil security—the fuel with the highest scarcity concerns and high import dependence in most countries, lacking substitutes in transport (see SI section 6.8.3.1.7).**

[b] **We designed a new indicator that can draw on existing model variables (see SI section 6.8.3.2).**

6.2.2 Choice of scenario data

Using model inter-comparison results from AMPERE allows us to take advantage of an internally consistent set of scenario specifications and harmonized input assumptions (Kriegler et al 2015, Riahi et al 2015). AMPERE work package 2 was chosen because (i) the data is publicly available, (ii) it consistently defines alternative short-term climate policy pathways across models until 2030, which is particularly relevant from an SDG perspective with a focus on short/medium-term developments, and (iii) it is the only model intercomparison project that combines different types of constraints with respect to the stringency of short-term climate policies and the availability of mitigation technologies or energy demand growth assumptions (see Table 6.3 and SI section 6.8.4). This is a key requirement for comprehensively exploring the SD risk dimensions of alternative 2°C pathways. Yet the reported data does not shed light on all relevant dimensions. One shortcoming is the simplifying assumption of regionally homogeneous carbon prices without consideration of burden sharing regimes. This impedes an analysis of regional mitigation cost distributions (see den Elzen et al 2008, Luderer et al 2012, Tavoni et al 2013, Aboumahboub et al 2014, Tavoni et al 2015) and related SD implications.

The analysis draws on more than 20 scenario specifications from seven models: DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, and WITCH (for further information, see Riahi et al (2015) and SI section 6.8.4). To avoid comparisons of scenario results from different sets of models, most figures only draw on a subset of models as (i) not all models ran or found a solution for all mitigation scenario specifications, and (ii) not all models report results for all indicators due to model type, assumptions on parameters and constraints, or respective system boundaries (see Table S-6.1). The results are presented similarly to the scenario ranges in the Working Group III contribution to the IPCC Fifth Assessment Report (WGIII AR5) because this shows variability across models. However, given that the sample size is small and no systematic variation of all relevant model input assumptions was performed this variability does not represent full model uncertainty.

Table 6.3 Naming of AMPERE mitigation scenarios (see Table S-6.3 and Riahi et al 2015 for details).

Model constraints	Description	Scenario name
Short-term targets (2030)		
Optimal policy	Emissions follow optimal 2°C pathway	‘OPT’
Low short-term target	High-ambition pathway (low short-term target): 53 Gt CO_2eq	‘LST’
High short-term target	Low-ambition pathway (high short-term target): 61 GtCO_2eq	‘HST’
Technology cases		
Full portfolio of technologies	Full portfolio of mitigation technologies	‘Full-Tech’
Low energy intensity[a]	Energy intensity improvements rate doubles	‘LowEI’
Limited biomass	Limited global potential for bioenergy (<100 EJ/yr)	‘LimBio’
No CCS	available CO_2 capture and storage never becomes available	‘NoCCS’
Limited solar/wind potential	Limited potential (<20% of regional electricity supply)	‘LimSW’
No new nuclear plants	No new nuclear capacity is added; older plants are retired	‘NucOff’

[a] LowEI scenarios assume lower final energy demand due to improvements in energy efficiency and behavioural changes so that equivalent levels of overall energy service are supplied with lower final energy. Due to the limited representation of end-use technologies in some models, many models represent this in a stylized way.

6.3 Results

The analysis is divided into two parts: we assess co-benefits of alternative 2°C pathways before turning to their mitigation risk profiles. In each part, we systematically analyze different clusters of 2°C pathways to understand the implications for SD outcomes of variations in (i) short-term climate policy stringency, (ii) availability of mitigation technologies or (iii) a combination of the two. Analyzing these clusters is highly relevant, because the current and projected INDC emission trajectories are not consistent with optimal 2°C pathways (UNFCCC 2015b) and the standard assumption of full technological flexibility is inhibited as significant upscaling of low-carbon technologies faces many different hurdles in practice[24]. Our analysis here focuses on the first half of the 21st century in which the interaction of short-term climate policies and the long-term climate target is strongest (Kriegler et al 2013, Luderer et al 2013, 2016, Riahi et al 2015, Eom et al 2015, Bertram et al 2015a).

6.3.1 Synergies across mitigation and sustainable energy objectives

Figure 6.1 uses cumulative indicators for (i) CO_2 emissions (Zickfeld et al 2012), (ii) the co-emitted air pollutants black carbon (BC) and sulphur dioxide (SO_2) and (iii) global oil extraction and trade as well as transport sector reliance on oil to present reduced SD risks, i.e. co-benefits of mitigation scenarios compared to baseline developments. Figure 6.1 shows that co-benefits in terms of lower ocean acidification, health and oil security increase relative to optimal 2°C pathways by limiting the availability of key mitigation technologies, though considerable differences exist for different technologies and different sustainable energy objectives. This is for three main reasons:

i. The unavailability of low-carbon technologies limits long-term mitigation potential, resulting in greater near-term emissions reduction requirements to meet a particular long-term climate goal. This leads to a decrease in fossil fuel use in the medium term (with lower cumulative global oil trade, oil extraction as well as transport sector reliance on oil) and the associated CO_2 emissions and co-emitted air pollutants. Limiting technologies that play a smaller role in reaching the long-term goal results in less dramatic transition requirements and fewer additional co-benefits.
ii. When relying less on bioenergy and/or CO_2 capture and storage (CCS) technologies, the models are forced to switch more rapidly from fossil fuels to solar, wind and nuclear energy, which have higher co-benefits for air quality and oil security (Bruckner et al 2014, Hertwich et al 2015).

[24] For example, CCS technology demonstration lags behind early IEA technology roadmaps (IEA 2009); nuclear power plant investments face high public acceptance challenges and even renewable energy (RE) investments are often opposed (Bruckner et al 2014). Unforeseen events or accidents (e.g., Fukushima) change risk perceptions of technologies (Rogers 1997, Patt and Weber 2014) making the analysis of limited mitigation technology portfolios interesting and relevant. To avoid unavailability of specific technologies, complementary technology policies (Somanathan et al 2014) could reduce additional costs (Kalkuhl et al 2013, Bertram et al 2015b) and ensure innovation activity, such as for CCS (von Stechow et al 2011) or PV (Peters et al 2012).

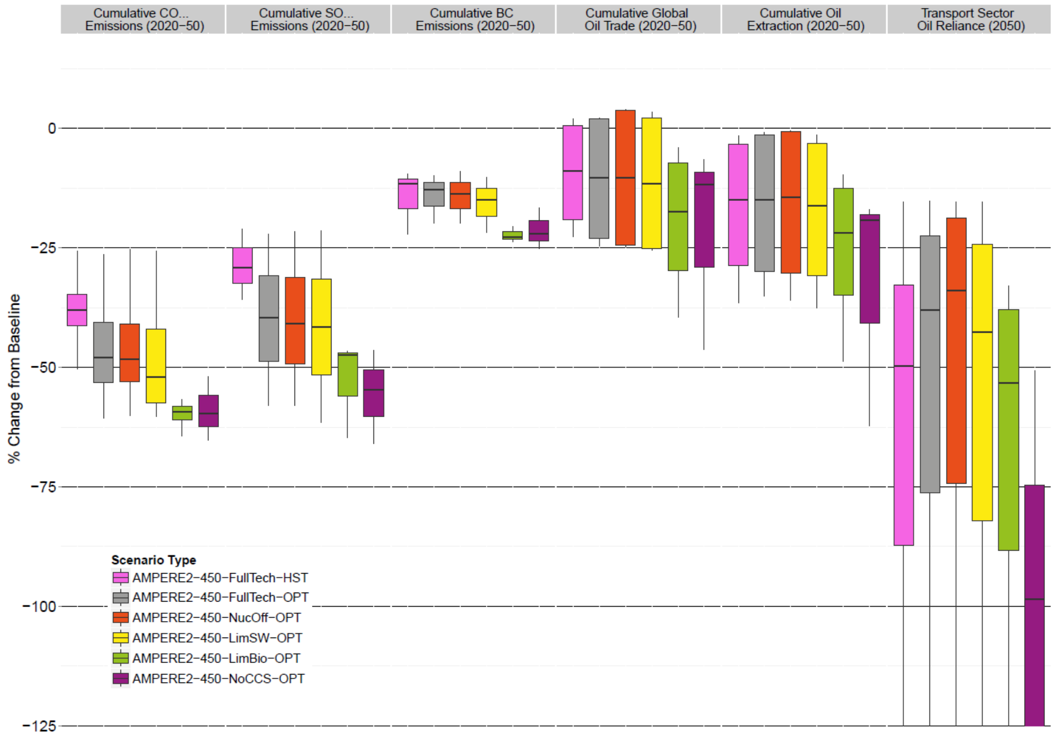

Figure 6.1 Percentage changes in indicators for co-benefits for reduced ocean acidification, air quality, oil security, and transport sector fuel diversity in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios assuming no new nuclear capacity (red), limited potential for solar and wind energy (yellow) limited global bioenergy potential (green) or unavailability of CCS (purple). The thick black lines show the median of results, the coloured ranges show the interquartile ranges and whiskers show the minimum and maximum results.

iii. Limiting the deployment of bioenergy or CCS technologies that are associated with co-emitted air pollutants themselves (see SI section 6.8.3.1.9) additionally reduces air pollutant emission levels —which is not the case for limiting the availability of non-combustible RE or new nuclear capacity.

Admittedly, these results only cover a small subset of potential co-benefits from mitigation. However, the literature suggests that this finding may apply more broadly (see von Stechow et al 2015 for a review and synthesis): climate policy that leads to less fossil fuel use and energy demand growth in the near term drives a broad range of co-benefits beyond air quality and oil security, such as reduced water use and pollution, reduced ecosystem impacts, reduced health impacts (also due to more physical activity under changed mobility patterns and less fuel poverty in insulated housing) as well as more local employment opportunities.

Comparing optimal 2°C pathways with scenarios assuming weak short-term climate policies confirms the positive effect of stringent mitigation in the near term on the magnitude of co-benefits (see Figure S-6.5 for the year 2030): weak short-term climate policies imply a reduction in co-benefits relative to those that could materialize in optimal 2°C pathways. This effect is, however, not as obvious for cumulative 2050 values (see Figure 6.1) because some of the additional mitigation efforts in the period 2030–2050 partially compensate for weak climate policies until 2030. Since the transport sector is characterized by faster capital turnover rates (at least with regard to the vehicle fleet) (Bertram et al 2015a), it can react more quickly to carbon price changes, compensating for higher emissions from sectors that are less flexible. This may lead, for example, to a higher fuel diversity in the transport sector in the year 2050 in delayed mitigation scenarios compared to optimal 2°C pathways albeit at high uncertainty.

6.3.2 Trade-offs between mitigation and sustainable energy objectives

While constraining a particular mitigation technology may minimize the mitigation risks specific to that technology, it usually implies an increase in the deployment of other low-carbon technologies, which may incur other mitigation risks. Figure 6.2 shows that limiting the availability of specific technologies in 2°C pathways with immediate global climate policies substantially increases the risk of not meeting other sustainable energy objectives. While the unavailability of CCS and limitation of bioenergy potential lead to the largest co-benefits (see Figure 6.1), they also entail significantly higher SD risks. This can be explained by the promise of greater flexibility in near-term emission pathways that are still able to meet the long-term climate goal through the presence of carbon dioxide removal technologies, such as bioenergy with CCS (BECCS). Constraining BECCS deployment by limiting the global bioenergy potential or ruling out CCS deployment results in substantially higher deployment of other mitigation technologies in the medium term. The increase is much less pronounced for limiting the potential for solar and wind energy or assuming no new nuclear capacity (see Figure S-6.6).

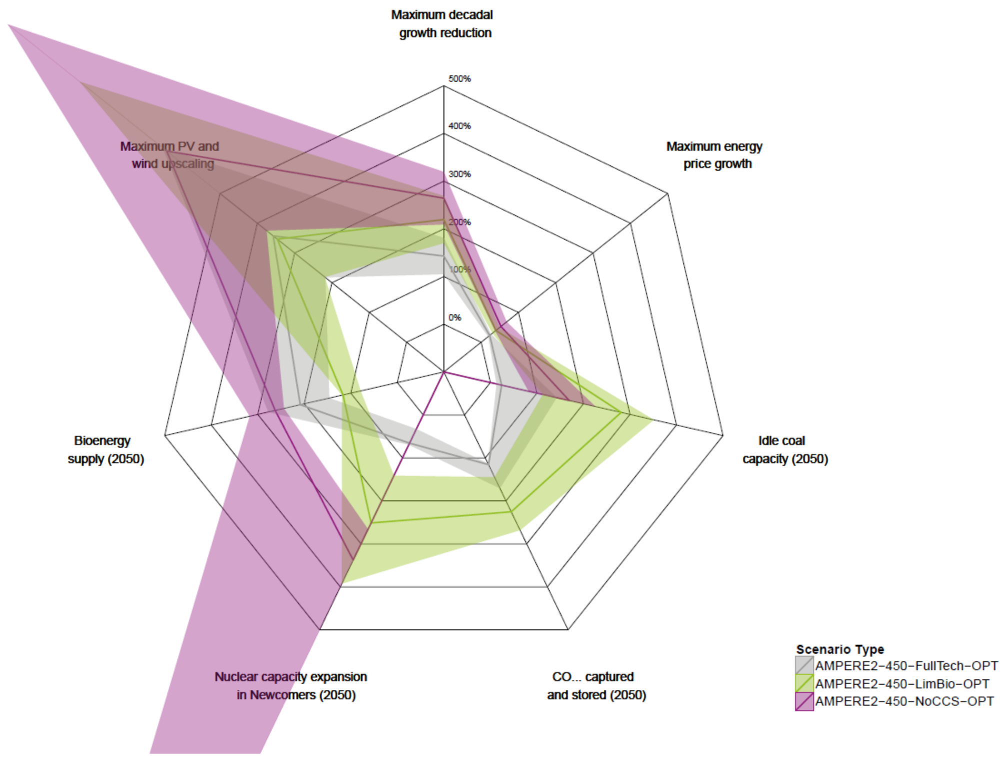

Figure 6.2 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for three integrated models (GCAM, MESSAGE, REMIND) relative to baseline scenarios and a CCS reference value, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey), with scenarios assuming limited global bioenergy potential (green) and unavailability of CCS (purple). Thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 6.2.2).

Due to the different nature of the mitigation risks, it is unclear how decreasing risks in one dimension (e.g. bioenergy expansion or environmental risks associated with CCS deployment), can be traded off with risk increases in others (e.g. transitional growth reduction, energy price growth, nuclear proliferation or the technological challenges of integrating high amounts of fluctuating RE into existing power grids in a very short time frame). For example, a 20%–30% increase in energy prices may have a much more immediate, adverse effect on the poor in many countries than a 4-7-fold increase in maximum decadal upscaling of variable renewable energy sources, which is primarily a technological and institutional challenge for infrastructure provision. Rather than aggregating effects across different risk dimensions, the purpose of this analysis is to make the trade-offs across alternative clusters of mitigation pathways transparent. Hence, the way the climate SDG is met can substantially alter the risks of not meeting other SDGs and sustainable energy objectives.

This is confirmed by Figure 6.3: delaying stringent mitigation in the near term leads to a significant increase in mitigation risk levels in the medium term compared to optimal 2°C pathways. With more GHG emissions before 2030, subsequent reductions are more expensive (Luderer et al 2013) and need to be faster to stay below 2°C (Eom et al 2015)—with implications for the grid integration of fluctuating RE (see SI section 6.8.3.1.6) and for stranded investments in coal capacity (Johnson et al 2015) and the associated job losses (Rozenberg et al 2014). The carbon lock-in effect hence manifests itself particularly in technological and economic risk dimensions. To a lesser degree, these effects can also be seen for delayed mitigation scenarios with more optimistic assumptions about short-term climate policies (see Figure S-6.7). Hence, delaying stringent mitigation implies forgoing potential paths with lower risks along multiple SD dimensions.

In contrast, assuming lower energy demand growth entails mitigation risk reductions relative to optimal 2°C pathways (see Figure 6.3). As each unit of energy not produced is free of pervasive supply-side risks, reducing energy demand by promoting energy efficiency in end-use sectors (e.g. consumer appliances), lifestyle changes (e.g. people living in higher-density areas and eating less dairy and meat) and structural changes in the economy (e.g. shifting to more service-oriented economies) is an important strategy both for mitigation and other sustainable energy objectives (von Stechow et al 2015).

Note that these reductions in energy demand growth are assumed to happen in the baseline scenarios, i.e. independent of the mitigation efforts and hence without a cost mark-up; it is unclear how future energy demand levels would develop under real-world conditions where clean energy and energy efficiency projects may compete for limited funds (McCollum et al 2013b). Furthermore, the models do not simply prescribe lower energy supply at the expense of energy service supply, but alter assumptions on the average energy intensity improvement rates and, e.g. on the viability of more compact, public transit-friendly urban areas (Riahi et al 2015). This does not imply, however, that all integrated models project final energy supplies in mitigation scenarios that are consistent with minimum thresholds of energy consumption to satiate basic needs related to cooking, heating, health and other infrastructure (Steckel et al 2013, Lamb and Rao 2015). Hence, projections of energy demand from individual models need to be interpreted with care (see discussion in SI section 6.8.2).

6.3.3 Trade-offs between mitigation and sustainable energy objectives for combined model constraints

As current GHG emission trends keep tracking along business-as-usual (Edenhofer et al 2014a) and societal concerns grow with regard to upscaling of many low-carbon technologies (see footnote 24), 2°C pathways with multiple constraints seem to mirror most closely developments observed in the real world. In fact, delaying stringent mitigation in combination with technological constraints risks no longer meeting the climate goal (Riahi et al 2015), substantially increases mitigation risks (see Figure 6.4) and increasingly jeopardizes our ability to manage risk trade-offs. For CCS and bioenergy whose unavailability/limitations already show substantial risk trade-offs in immediate mitigation scenarios, most models can no longer find a solution (for CCS unavailability only DNE21+ and GCAM; for limited global bioenergy potential only GCAM, POLES, and REMIND) implying a high risk of not meeting the 2°C target.

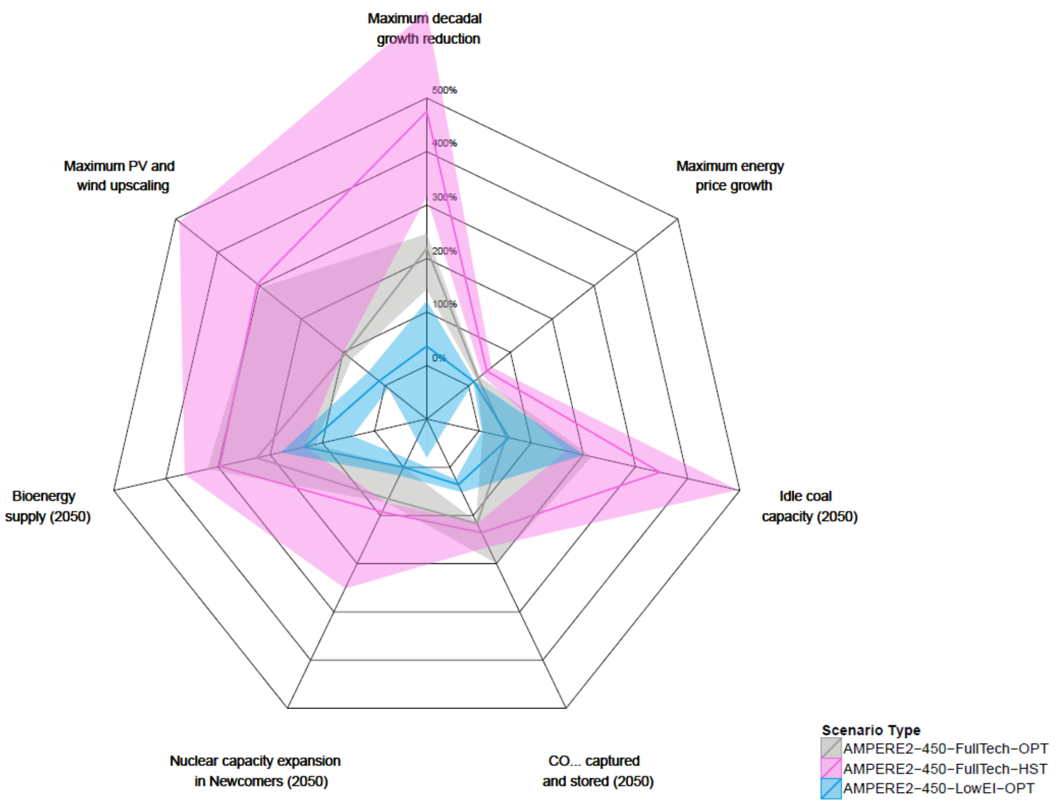

Figure 6.3 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios and a CCS reference value, comparing immediate (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 6.2.2).

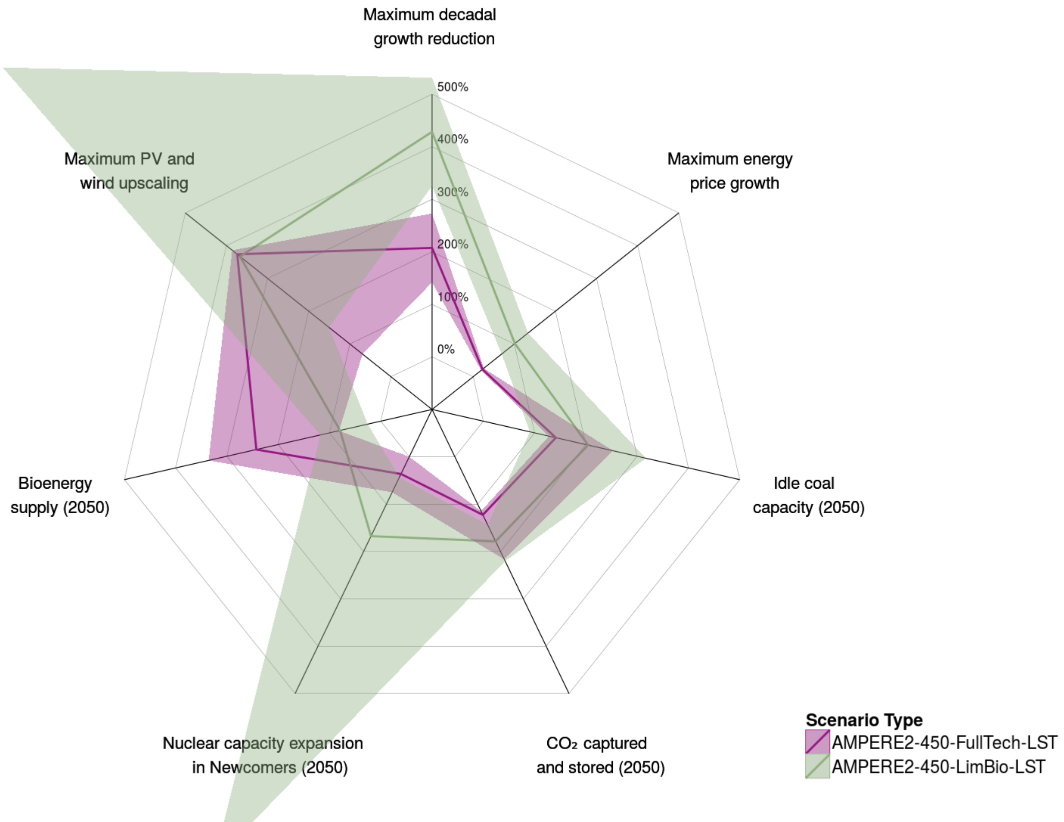

Figure 6.4 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios and a CCS reference value, comparing delayed mitigation scenarios assuming full availability of mitigation technologies and weak short-term climate policies (purple) with delayed mitigation scenarios assuming limited global availability of bioenergy (green). Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 6.2.2).

Figure 6.4 draws on AMPERE scenarios with multiple constraints but shows results for more optimistic —albeit not optimal — short-term climate policies[25], with and without limited global bioenergy potential. As models work close to their feasibility frontier, the additional constraint results in large mitigation risk increases. Even for non-biomass RE and nuclear energy, whose limitation/phase-out has rather small effects in immediate 2°C pathways, risk trade-offs increase strongly for delayed mitigation scenarios in some dimensions (see Figures S-6.7 and S-6.8).

6.4 Discussion

This letter presents a first attempt to shed light on the question of how alternative 2°C pathways perform in non-climate SD dimensions and to draw conclusions about important interactions between stringent mitigation and other sustainable energy objectives. Figure 6.5 shows an overview of the different clusters of constrained 2°C pathways relative to (each model's) optimal pathways (i.e. those with immediate mitigation, full technology portfolios, and conventional energy demand growth). We use

[25] Figure 6.4 shows 'LST' scenarios (i.e. with more optimistic assumptions about near-term climate policies relative to 'HST' scenarios but still less stringent than optimal, see Table 6.1) because only three models (GCAM, POLES, and REMIND) were able to find a solution for the 'HST-LimBio' scenarios.

'optimal' scenarios as benchmarks because they show comparatively balanced risk profiles relative to baseline developments (see Figures 6.2–6.4) and because they are commonly used as reference point for policy analysis, e.g. in the WGIII AR5 (Edenhofer et al 2014a). This enables the comparison of the various SD implications of one cluster of 2°C pathways to those of all others and therefore facilitates an informed public debate on socially acceptable SD risks and thus the interaction between the international climate policy and the broader SDG agendas.

Note that 'optimal' pathways are not necessarily the most socially desirable because they may already involve unacceptable risks. Scientific analysis alone cannot judge whether a particular 2°C pathway poses acceptable or unacceptable risks to society (Edenhofer and Minx 2014). Science can, however, explore alternative mitigation pathways and inform an enlightened public debate across SD risk dimensions in an iterative learning process (Edenhofer and Kowarsch 2015). For example, annual bioenergy supply is projected to reach up to 168 EJ (median: 158 EJ) in 2050 in optimal scenarios. These levels of biomass extraction may already be associated with fundamental challenges with respect to food security, place-specific livelihoods, water availability and biodiversity (Creutzig et al 2012, Smith et al 2014). These numbers further increase substantially over the second half of the century, reaching up to 862 EJ (median: 268 EJ) with growing requirements for removing CO_2 from the atmosphere via bioenergy with CCS (BECCS) technologies in many available scenarios (Clarke et al 2014). Many 'optimal' 2°C pathways have therefore been challenged on these grounds (Fuss et al 2014, Smith et al 2016).

In a world which is increasingly unlikely to develop along 'optimal' scenario trajectories, an informed public debate about synergies and risk trade-offs implied by alternative clusters of constrained 2°C pathways is key for identifying those which are socially acceptable. For example, current INDCs at best add up to emission trajectories similar to those 2°C pathways with low short-term ambition ('LST' scenarios, see Table 6.3)[26]. According to Figure 6.5, these pathways (presented as circles) not only lead to fewer co-benefits compared to optimal 2°C pathways (except for cumulative BC emissions and transport sector oil reliance) but also to significantly higher mitigation risk levels, particularly in socioeconomic dimensions—with higher risks of not meeting those SDGs related to economic growth, energy access, job preservation, food security and resilient grid infrastructure (see also Figure S-6.7).

When a technology constraint is added, only the risks specific to that technology can be lowered (e.g. reduced nuclear proliferation risks for scenarios with no new nuclear capacity or fewer grid integration challenges for scenarios with limited potential for solar and wind energy, see also Figures S-6.8 and S-6.9). The other risk levels are exacerbated, particularly for those SDGs that relate to economic growth, job preservation, resilient infrastructure, and ocean acidification. This is particularly obvious for scenarios with limited global potential of bioenergy in which the risks related to bioenergy expansion are lower (including environmental effects related to BECCS

[26] See http://infographics.pbl.nl/indc and http://climateactiontracker.org/global.

deployment) but the risks of not meeting socioeconomic SDGs are significantly higher (see green circles in Figure 6.5). Limiting the global use of bioenergy to 100 EJ per year by 2050—widely believed to be more sustainable (Creutzig et al 2014)—hence introduces a trade-off with socioeconomic objectives for weak short-term climate policies.

While there are uncertainties around acceptable levels of bioenergy deployment, the development and deployment of CCS technology is lagging behind expectations (IEA 2009), despite its important role in keeping mitigation costs at relatively low levels (Edenhofer et al 2014a). Our results highlight two things: first, those models that are flexible enough to compensate for the unavailability of CCS can only do so with increased upscaling requirements for other low-carbon technologies and related SD risks (see pink circles in Figure 6.5). This also implies high near-term mitigation requirements with associated co-benefits. Second, the absence of CCS seriously questions the achievability of the 2°C target in a world with delayed climate action and therefore threatens the climate SDG itself—only two models can report results for the combination with weak short-term climate policies.

In contrast, 2°C pathways with lower energy demand growth generally entail a substantial reduction in SD risk levels (blue shapes in Figure 6.5). This confirms results from a bottom-up assessment of the wider SD implications of technology-specific studies from a cross-sectoral perspective (von Stechow et al 2015). While these scenarios typically do not feature many additional co-benefits due to lower supply-side transition requirements, achieving lower energy demand growth has considerable synergies with the SDG agenda related to economic growth, food security, resilient grid infrastructure as well as with the peaceful use of nuclear energy. Delaying mitigation in scenarios with low energy demand growth only entails moderate risk increases—although some co-benefits are reduced and more coal capacity is likely to be retired early. Pursuing aggressive energy efficiency improvements across all sectors and rethinking high-energy lifestyles therefore seems essential to increase synergies and keep the trade-offs across SDGs manageable in a world that is characterized by multiple constraints. Unfortunately, model inter-comparison projects have not yet analyzed the combination of technology constraints and low energy demand growth pathways, which is a promising research area to better understand synergies between SDGs. Future research should also ensure that mitigation scenarios are consistent with minimum thresholds of energy demand necessary to satiate basic human needs (see discussion in SI section 6.8.2).

This letter has analyzed the changes in SD risks across alternative 2°C pathways. These effects depend to a great extent on the development context, i.e. assumptions about baseline developments (Moss et al 2010, O'Neill et al 2014). To circumvent this potential caveat, the analysis used AMPERE data that stands out in its comprehensive effort to harmonize future socio-economic drivers of SD across models in the baseline scenarios: e.g. regional-level gross domestic product (GDP), population, and energy demand growth. This makes the results more comparable across models but begs the question of how the results would have changed for alternative assumptions beyond changes in energy demand growth. Research can and should build on alternative baseline developments as expressed by the 'shared socioeconomic pathways' (O'Neill et al 2014) that will soon be published even though important, non-trivial discussions remain on how SDGs can be adequately built into these baselines (O'Neill et al 2017).

Indicators that were used to track the changes in SD risks are only rough and sometimes very rough approximations of individual SDGs. There is no doubt that individual models—particularly those coupled to a detailed agro-economic and land-use model—could already provide better indicators, such as for water availability and ecosystem impacts which are important concerns in stringent mitigation pathways (see SI section 6.8.3.1.1). However, these have not yet been analyzed in a multi-model study (von Stechow et al 2015). We believe that such inter-model comparison results are crucial for a meaningful public debate about SD risks.

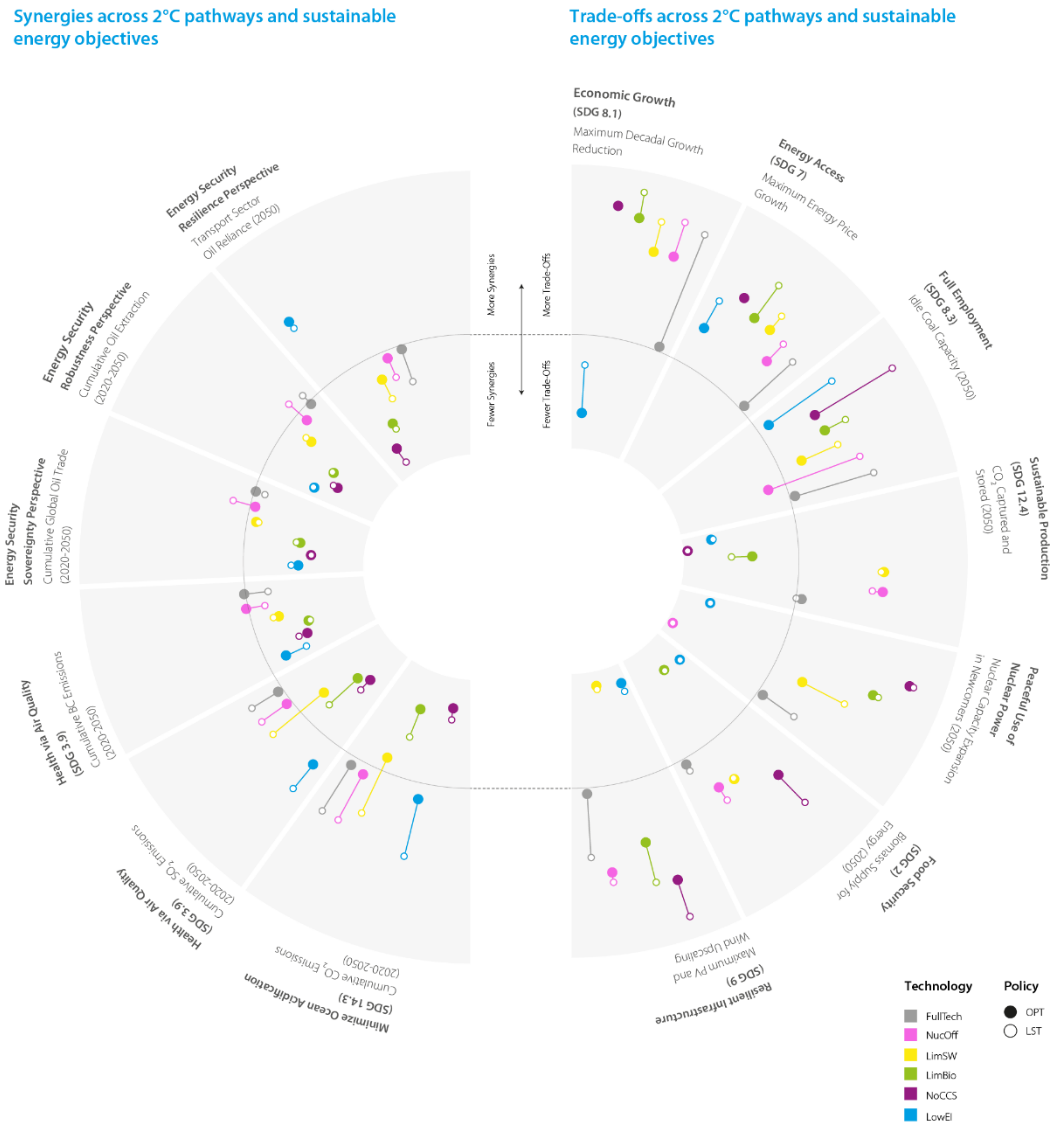

Figure 6.5 Percentage changes in SD risk dimensions that can be linked to a set of SDGs and other sustainable energy objectives in constrained 2°C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth). The different shapes denote different short-term climate policy stringencies while the different colours denote different technology cases (see Table 6.3). As the figure aims at showing trends in synergies and risk trade-offs of alternative clusters of 2°C pathways rather than an exact quantitative analysis, results are plotted in logarithmic scale (see Table S-6.4 for the underlying data).

Another important caveat of the analysis is that we focus on 2050 and the preceding decades when looking at the implications of alternative 2°C pathways for SD risk dimensions. The risks of some 2°C pathways, however, only unfold later in that century when some particularly risky negative emissions technologies, such as BECCS, are being deployed at large scale to compensate for lower mitigation efforts in the first decades and residual GHG emissions in other sectors (Fuss et al 2014, Smith et al 2016). For illustrative purposes, Figures S-6.10 and S-6.11 show how mitigation risks change from 2050 to 2080 for scenarios with substantially different amounts of negative emission requirements. Since the AMPERE scenario specifications do not allow for a meaningful comparison across scenarios with low or high amounts of negative emissions, we use the amount of radiative forcing overshoot to cluster scenarios with respect to their dependence on negative emissions (also used in the WGIII AR5 scenario database, see Krey et al 2014). It shows that the magnitude of the mitigation risk levels can change substantially over time for those dimensions that are related to negative emission technologies such as CCS and bioenergy deployment.

Our analysis points to important future challenges: first, the chosen indicators do not represent all SDGs as some touch on socio-cultural and institutional aspects which are challenging—if not impossible—to represent in an economic model framework (see SI section 6.8.2). Second, the changes in the indicators across scenarios are merely indicative for the change in risks to meet the related SDGs and sustainable energy objectives because there are many more relevant drivers that cannot be analyzed based on the available scenario data. Third, many relevant issues play out at lower geographic and time scales which are difficult to represent adequately in global-scale integrated models. For example, food security is driven by many socioeconomic drivers both on global and local scales and bioenergy expansion represents but one of those (Tscharntke et al 2012). And according to Creutzig et al (2012), the models are not (yet) suitable for operationalizing important global SD dimensions of bioenergy supply such as the socioeconomic convergence across different countries. Nevertheless, we argue that the indicators used in this letter are relevant for evaluating additional pressure on the energy-economy-climate system from additional constraints as represented in the models. As such, they supply important information from internally consistent model frameworks taking into account inter-sectoral and inter-regional interactions (von Stechow et al 2015 and SI section 6.8.1).

We provide this early contribution to a public debate on the relationship between the international climate policy and the SDG agendas based on existing multi-model scenario data that was not specifically developed for this particular purpose. This stimulus seems important because results from model intercomparisons that are tailored towards the SDG-climate nexus will not be published for some years. Only by working with the available data can we start discussing relevant (risk) trade-offs and synergies. Based on our analysis, we argue that SD considerations are central for determining socially acceptable climate policies and that the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Moreover, experiences and caveats of this analysis can help guide future research efforts at a relevant moment in time when new model comparison exercises are being designed. For example, to remain policy-relevant, SDG-focused multi-model comparisons will need to address inequality, poverty, and basic human needs as major drivers of the policy process much more adequately. This requires a serious discussion, e.g. on how to deal with the coarse regional disaggregation in the integrated modeling frameworks. Equally, successful efforts to address SDG-relevant issues in one model, e.g. for the analysis of water availability or ecosystem impacts (see SI section 6.8.2), will need to be lifted into a multi-model context.

6.5 Conclusion

Until now, no multi-model study has been used to systematically analyze the changes in SD risks implied by stringent mitigation scenarios and evaluate them across a set of SDGs. This letter addresses this research gap by analyzing a comprehensive set of alternative clusters of 2°C pathways consistently formulated across many integrated models from the AMPERE model inter-comparison study, drawing on publicly available scenario results to calculate indicators for global SD risks. We shed light on the implications of alternative clusters of 2°C pathways for meeting a set of energy-related SDGs and other sustainable energy objectives and to inform the public debate about the synergies and trade-offs across the international climate policy and the SDG agendas.

Our analysis shows that the near-term choice of 2°C pathways has implications for the extent of synergies and trade-offs across energy-related SDGs in the medium term. Given current trends in emissions and technology deployment, we argue that mitigation pathways are likely to be characterized by multiple constraints. But adding limits on the availability of specific mitigation technologies on top of weak short-term climate policies decreases synergies and locks in substantial trade-offs across environmental and socioeconomic objectives. From an SDG perspective, the challenges of meeting other sustainable energy objectives substantially change with the way the climate SDG will be met. In some cases, meeting the 2°C target is even threatened itself. Achieving low-energy demand growth, e.g. through aggressive energy efficiency improvements, helps to manage these trade-offs and attain multiple energy-related SDGs together. We find the greater the constraints on flexibility in meeting the 2°C target, the higher the risks of not meeting other SDGs and the flexibility to manage these risks. Governments at all levels need to be informed about such implications of their collective decision for the attainability of global SDGs. This could avoid additional pressures on the sustainability of each region's development pathway.

After COP21, decision makers need to rethink their commitment to the SDG agenda, given that the short-term ambition for mitigation action falls short of the mitigation efforts consistent with staying below 2°C in a cost-effective way. According to our results, this is likely to decrease co-benefits and increase the risks for attaining energy-related SDGs and other sustainable energy objectives. Since many of these SD risks are best dealt with at the global level, however, they might be good entry points into additional incentives for international cooperation. We suggest that the review of INDCs should provide for an assessment of policies at all scales to monitor global risks for non-climate sustainability objectives that arise from specific global mitigation pathways.

Monitoring these risks could avoid unintended consequences (which might even delegitimize the 2°C target), finding new entry points for global cooperation and providing rationales for ramping up mitigation ambition in the short to medium term.

Future research should extend the current system boundaries and, based on a comprehensive review of model literature on the climate-SDG nexus, establish indicators that help evaluate integrated policies addressing multiple SDGs in a unified framework. This would be a prerequisite for model inter-comparison projects with a focus on the interactions across multiple SDGs that could result in meaningful and robust results for better decision making. Climate policy will not be successful unless it seriously considers other policy objectives and therefore wider SD implications. Dividing the huge effort of achieving more sustainable development pathways into isolated policy problems will fall short of reaping synergies and successfully managing trade-offs across the many SDGs.

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6.7 References

Aboumahboub T, Luderer G, Kriegler E, Leimbach M, Bauer N, Pehl M and Baumstark L 2014 On the regional distribution of climate mitigation costs: the impact of delayed cooperative action *Clim. Change Econ*. **05** 1440002

Arnell NW, van Vuuren DP and Isaac M 2011 The implications of climate policy for the impacts of climate change on global water resources *Global Environmental Change* **21** 592–603

Bauer N, Mouratiadou I, Luderer G, Baumstark L, Brecha RJ, Edenhofer O and Kriegler E 2013 Global fossil energy markets and climate change mitigation—an analysis with REMIND Clim. Change 1–14

Bertram C, Johnson N, Luderer G, Riahi K, Isaac M and Eom J 2015a Carbon lock-in through capital stock inertia associated with weak near-term climate policies *Technol. Forecast. Soc. Change* A **90** 62–72

Bertram C, Luderer G, Pietzcker RC, Schmid E, Kriegler E and Edenhofer O 2015b Complementing carbon prices with technology policies to keep climate targets within reach *Nat. Clim. Change* **5** 235–9

Bonsch M et al 2016 Trade-offs between land and water requirements for large-scale bioenergy production *Glob. Change Biol. Bioenergy* **8** 11–24

von Braun J et al 2008 *High Food Prices: The What, Who, and How of Proposed Policy Actions* (Washington, DC: International Food Policy Research Institute)

Bruckner T et al 2014 Energy systems *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 511–97

Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J 2014 Trade-offs of different land and bioenergy policies on the path to achieving climate targets *Clim. Change* **123** 691–704

Cherp A, Jewell J, Vinichenko V, Bauer N and DeCian E 2016 Global energy security under different climate policies, GDP growth rates and fossil resource availabilities *Clim. Change* **136** 83–94

Clarke L et al 2014 Assessing transformation pathways *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 413–506

Creutzig F et al 2014 Bioenergy and climate change mitigation: an assessment *GCB Bioenergy* 7 916–44

Creutzig F, von Stechow C, Klein D, Hunsberger C, Bauer N, Popp A and Edenhofer O 2012 Can bioenergy assessments deliver? *Economics of Energy & Environmental Policy* **1** 65–82

Daioglou V, van Ruijven BJ and van Vuuren DP 2012 Model projections for household energy use in developing countries *Energy* **37** 601–15

De Fraiture C, Giordano M and Liao Y 2008 Biofuels and implications for agricultural water use: blue impacts of green energy *Water Policy* **10** 67–81

den Elzen MGJ, Lucas PL and van Vuuren DP 2008 Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations *Clim. Change* **90** 243–68

Drouet L, Bosetti V and Tavoni M 2015 Selection of climate policies under the uncertainties in the fifth assessment report of the IPCC *Nat. Clim. Change* **5** 937–40

Edenhofer O and Kowarsch M 2015 Cartography of pathways: a new model for environmental policy assessments Environ. *Sci. Policy* **51** 56–64

Edenhofer O and Minx J 2014 Mapmakers and navigators, facts and values *Science* **345** 37–8

Edenhofer O et al 2014a Technical summary *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 31–107

Edenhofer O, Kadner S, von Stechow C, Schwerhoff G and Luderer G 2014b Linking climate change mitigation research to sustainable development *Handbook of Sustainable Development* 2nd edn ed G Atkinson, S Dietz, E Neumayer and M Agarwala (Cheltenham, UK: Edward Elgar) pp 476–99

Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, Riahi K and van Vuuren DP 2015 The impact of near-term climate policy choices on technology and emission transition pathways *Technological Forecasting and Social Change* **90** 73–88

Fleurbaey M et al 2014 Sustainable development and equity *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 283–350

Fuss S et al 2014 Betting on negative emissions *Nature Clim. Change* 4 850–3

Griggs D, Stafford-Smith M, Gaffney O, Rockström J, Öhman MC, Shyamsundar P, Steffen W, Glaser G, Kanie N and Noble I 2013 Policy: sustainable development goals for people and planet *Nature* **495** 305–7

Hejazi M I, Edmonds J, Clarke L, Kyle P, Davies E, Chaturvedi V, Eom J, Wise M, Patel P and Calvin K 2013 Integrated assessment of global water scarcity over the 21st century: 2. Climate change mitigation *policies Hydrology and Earth System Sciences Discussions* **10** 3383–425

Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, Heath GA, Bergesen JD, Ramirez A, Vega MI and Shi L 2015 Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies *Proc. Natl Acad. Sci. USA* **112** 6260–4

IEA 2009 *Technology Roadmap: Carbon Capture and Storage* (Paris, France: Organisation for Economic Co-operation and Development/International Energy Agency (IEA)) (https://iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2009.html)

Jakob M and Edenhofer O 2014 Green growth, degrowth, and the commons *Oxford Review of Economic Policy* **30** 447–68

Jewell J, Cherp A and Riahi K 2014 Energy security under decarbonization scenarios: an assessment framework and evaluation under different technology and policy choices *Energy Policy* **65** 743–60

Jewell J, Cherp A, Vinichenko V, Bauer N, Kober T, McCollum DL, van Vuuren DP and van der Zwaan B 2013 Energy security of China, India, the EU and the US under long-term scenarios: results from six IAMs *Clim. Change Econ.* **4** 1340011

Johnson N, Krey V, McCollum DL, Rao S, Riahi K and Rogelj J 2015 Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants *Technol. Forecast. Soc. Change* A **90** 89–102

Joos F, Fröhlicher TL, Steinacher M and Plattner G-K 2011 Impact of climate change mitigation on ocean acidification projections *Ocean Acidification* ed J-P Gattuso and L Hansson (Oxford: Oxford University Press) pp 272–90

Kalkuhl M, Edenhofer O and Lessmann K 2013 Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? *Resour. Energy Econ.* **35** 217–34

Kim SH, Wada K, Kurosawa A and Roberts M 2014 Nuclear energy response in the EMF27 study *Clim. Change* **123** 443–60

Krey V et al 2014 Annex II: Metrics & Methodology *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 1281–328

Krey V, O'Neill BC, van Ruijven B, Chaturvedi V, Daioglou V, Eom J, Jiang L, Nagai Y, Pachauri S and Ren X 2012 Urban and rural energy use and carbon dioxide emissions in Asia *Energy Economics* **34** S272–83

Kriegler E et al 2015 Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy *Technol. Forecast. Soc. Change* A **90** 24–44

Kriegler E et al 2013 What does the 2°C target imply for a global climate agreement in 2020? The limits study on Durban Platform scenarios *Clim. Change Econ*. **04** 1340008

Kriegler E et al 2014 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies *Clim. Change* **123** 353–67

Kunreuther H et al 2014 Integrated risk and uncertainty assessment of climate change response policies *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 151–205

Kunreuther H, Heal G, Allen M, Edenhofer O, Field CB and Yohe G 2013 Risk management and climate change *Nature Clim. Change* **3** 447–50

Lamb WF and Rao ND 2015 Human development in a climate-constrained world: what the past says about the future *Glob. Environ. Change* **33** 14–22

Lehtveer M and Hedenus F 2015 Nuclear power as a climate mitigation strategy—technology and proliferation risk *J. Risk Res*. **18** 273–90

Lotze-Campen H et al 2014 Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison *Agricultural Economics* **45** 103–16

Luderer G, Bertram C, Calvin K, DeCian E and Kriegler E 2016 Implications of weak near-term climate policies on long-term mitigation pathways *Clim. Change* **136** 127–140

Luderer G, DeCian E, Hourcade J-C, Leimbach M, Waisman H and Edenhofer O 2012 On the regional distribution of mitigation costs in a global cap-and-trade regime *Clim. Change* **114** 59–78

Luderer G, Pietzcker RC, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013 Economic mitigation challenges: How further delay closes the door for achieving climate targets Environ. Res. Lett. **8** 034033

McCollum D, Bauer N, Calvin K, Kitous A and Riahi K 2014 Fossil resource and energy security dynamics in conventional and carbon-constrained worlds *Clim. Change* **123** 413–26

McCollum DL, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013a Climate policies can help resolve energy security and air pollution challenges *Clim. Change* **119** 479–94

McCollum D, Nagai Y, Riahi K, Marangoni G, Calvin K, Pietzcker R, van Vliet J and van der Zwaan B 2013b Energy investments under climate policy: a comparison of global models *Clim. Change Econ*. **04** 1340010

Moss RH et al 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R and van Vuuren DP 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

O'Neill BC et al 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42**: 169–180

Pachauri S, van Ruijven BJ, Nagai Y, Riahi K, van Vuuren DP, Brew-Hammond A and Nakicenovic N 2013 Pathways to achieve universal household access to modern energy by 2030 *Environ. Res. Lett*. **8** 024015

Paltsev S and Capros P 2013 Cost concepts for climate change mitigation *Clim. Change Econ.* **04** 1340003

Patt AG and Weber EU 2014 Perceptions and communication strategies for the many uncertainties relevant for climate policy *WIREs Clim Change* **5** 219–32

PBL 2012 Roads from Rio+20 Pathways to achieve global sustainability goals by 2050 (The Hague, The Netherlands: Netherlands 3 Environmental Assessment Agency (PBL)) (http://pbl.nl/en/publications/2012/roads-from-rio20)

Peters M, Schneider M, Griesshaber T and Hoffmann VH 2012 The impact of technology-push and demand-pull policies on technical change—does the locus of policies matter? *Research Policy* **41** 1296–308

Popp A et al 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options *Clim. Change* **123** 495–509

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A and Schlosser A 2012 Using land to mitigate climate change: hitting the target, recognizing the trade-offs *Environ. Sci. Technol*. **46** 5672–9

Riahi K et al 2015 Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals *Technol. Forecast. Soc. Change* A **90** 8–23

Riahi K et al 2012 Energy pathways for sustainable development *Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press, and Laxenburg, Austria: International Institute for Applied Systems Analysis) Ch 17, pp 1203–306 (www.globalenergyassessment.org)

Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V and Riahi K 2015 Energy system transformations for limiting end-of-century warming to below 1.5°C *Nature Clim. Change* **5** 519–27

Rogelj J, McCollum DL, O'Neill BC and Riahi K 2013a 2020 emissions levels required to limit warming to below 2°C *Nature Clim. Change* **3** 405–12

Rogelj J, McCollum DL, Reisinger A, Meinshausen M and Riahi K 2013b Probabilistic cost estimates for climate change mitigation *Nature* **493** 79–83

Rogelj J, Schaeffer M, Meinshausen M, Shindell DT, Hare W, Klimont Z, Velders GJM, Amann M and Schellnhuber HJ 2014 Disentangling the effects of CO_2 and short-lived climate forcer mitigation *Proc. Natl Acad. Sci. USA* **111** 16325–30

Rogers GO 1997 The dynamics of risk perception: how does perceived risk respond to risk events? *Risk Anal*. **17** 745–57

Rogner H-H et al 2012 Energy Resources and Potentials *Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press, and Laxenburg, Austria: International Institute for Applied Systems) Ch 7, pp 423–512 (www.globalenergyassessment.org)

Rose SK, Richels R, Smith S, Riahi K, Strefler J and van Vuuren DP 2014 Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios *Clim. Change* **123** 511–25

Rozenberg J, Vogt-Schilb A and Hallegatte S 2014 Transition to clean capital, irreversible investment and stranded assets *World Bank Policy Research Working Paper* 6859 (https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2433812)

van Ruijven BJ, Schers J and van Vuuren DP 2012 Model-based scenarios for rural electrification in developing countries *Energy* **38** 386–97

Sathaye J et al 2011 Renewable energy in the context of sustainable development *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 707–89

Slovic P 1987 Perception of risk *Science* 236 280–5

van Sluisveld MAE, Harmsen JHM, Bauer N, McCollum DL, Riahi K, Tavoni M, van Vuuren DP, Wilson C and van der Zwaan B 2015 Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change *Global Environmental Change* **35** 436–49

Smith P et al 2014 Agriculture, forestry and other land use (AFOLU) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 811–922

Smith P et al 2016 Biophysical and economic limits to negative CO_2 emissions *Nature Clim. Change* **6** 42–50

Somanathan E et al 2014 National and sub-national policies and institutions *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 1141–205

von Stechow C et al 2015 Integrating global climate change mitigation goals with other sustainability objectives: a synthesis *Ann. Rev. Environ. Res*. **40** 363–94

von Stechow C, Watson J and Praetorius B 2011 Policy incentives for carbon capture and storage technologies in Europe: a qualitative multi-criteria analysis *Glob. Environ. Change* **21** 346–57

Steckel JC, Brecha RJ, Jakob M, Strefler J and Luderer G 2013 Development without energy? Assessing future scenarios of energy consumption in developing countries *Ecological Economics* **90** 53–67

Strefler J, Luderer G, Kriegler E and Meinshausen M 2014 Can air pollutant controls change global warming? *Environ. Sci. Policy* **41** 33–43

Tavoni M et al 2013 The distribution of the major economies' effort in the Durban Platform scenarios *Clim. Change Econ*. **04** 1340009

Tavoni M et al 2015 Post-2020 climate agreements in the major economies assessed in the light of global models *Nature Clim. Change* **5** 119–26

Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J and Whitbread A 2012 Global food security, biodiversity conservation and the future of agricultural intensification *Biological Conservation* **151** 53–9

UNFCCC 2015a Adoption of the Paris Agreement Proposal by the President (Paris: United Nations Framework Convention on Climate Change (UNFCCC)) (http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008831)

UNFCCC 2015b Synthesis report on the aggregate effect of the Intended Nationally Determined Contributions. Note by the secretariat. Report of the Ad Hoc Working Group on the Durban Platform for Enhanced Action (Paris: United Nations Framework Convention on Climate Change (UNFCCC)) (http://unfccc.int/resource/docs/2015/cop21/eng/07.pdf)

van Vuuren DP et al 2015 Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model *Technol. Forecast. Soc. Change* **98** 303–23

Wilson C, Grubler A, Bauer N, Krey V and Riahi K 2013 Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change* **118** 381–95

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith SJ, Janetos A and Edmonds J 2009 Implications of limiting CO_2 concentrations for land use and energy *Science* **324** 1183–6

Wise M, Dooley J, Luckow P, Calvin K and Kyle P 2014 Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century *Appl. Energy* **114** 763–73

Zickfeld K, Arora VK and Gillett NP 2012 Is the climate response to CO_2 emissions path dependent? *Geophys. Res. Lett*. **39** L05703

6.8 Supplementary Information

The supplementary information (SI) is structured as follows: SI section 6.8.1 provides a brief introduction into energy-economy-climate models, their differences and the rationale for model inter-comparison projects. SI section 6.8.2 gives an overview of important limitations of integrated models to address implications for some non-climate sustainability objectives. SI section 6.8.3 explains the link between a set of energy-related SDGs and other sustainable energy objectives, SD risks and associated indicators used in the analysis. SI section 6.8.4 lays out the main advantages of the model inter-comparison project AMPERE for such analysis. Supplementary figures and data are shown in SI section 6.8.5.

6.8.1 Integrated energy-economy-climate models

Integrated energy-economy-climate models, also often referred to as Integrated Assessment Models (IAMs), are computer-based tools to better understand the interactions between the economy, energy (in physical and economic terms) and often land-use systems as well as their effects on climate change. To explore the implications of alternative pathways in a range of plausible environments, they integrate insights from different disciplines and draw on models of both biogeophysical and human processes over long-time horizons (Hourcade *et al* 2006, van Vuuren *et al* 2009, Edenhofer *et al* 2014). For example, they use information about energy resources, technologies, and investments as well as (land-use) emissions. The scenario results on which this letter's analysis is based are derived from seven different integrated energy-economy-climate models that took part in the AMPERE project (see SI section 6.8.4). They span a diversity of modeling approaches with respect to functional structures and parametric assumptions (Riahi *et al* 2015). Table S-6.1 summarizes some of the main differences across the different models to the extent that they are relevant for our analysis. Please refer to Riahi *et al* (2015), the AMPERE website (http://ampere-project.eu) and the AMPERE scenario database for further information on the individual models and the scenario results they supplied.

The IAM community regularly organizes model inter-comparison projects in which efforts are made to harmonize key input parameters and to make model outputs comparable (Kriegler *et al* 2015b, Weyant *et al* 2006). As differences persist, a range of outcomes is plausible (Kriegler *et al* 2015a). To understand which results are robust across different models, we follow the approach of comparing results from multiple models in this letter. To circumvent climate system uncertainties with respect to the temperature response due to a given GHG emission scenario, the integrated models considered here usually calculate mitigation scenarios whose emission pathways meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. The uncertainty reflected in their results (represented by the ranges in Figures 6.1-6.4 and S-6.3-S-6.11) is hence distinct from the uncertainty of the change in the global temperature due to different emission scenarios (see Section 6.3.2.6 in Clarke *et al* 2014). The models analyzed here belong to a type of IAM that is based on cost-effectiveness analysis (CEA) and has to be differentiated from cost-benefit analysis (CBA)-based IAMs which are more controversial, e.g. in their attempt to determine optimal climate goals (Edenhofer *et al* 2014).

Also due to this coordinated research effort, the scenario results have been an important contribution to the IPCC WGIII (e.g. Fisher *et al* 2007, Fischedick *et al* 2011, Clarke *et al* 2014) and other global environmental science assessments (GEA 2012, UNEP 2014). Many of the widely held views about the requirements to meet the 2°C target stem from their insights, e.g. the GHG emissions reductions goals of 80-95% in developed countries below 1990 levels by 2050 (Knopf and Geden 2014).

Table S-6.1 Key characteristics and representation of multiple sustainability objectives for the global integrated model frameworks used in the analysis (partly derived from Krey *et al* 2014, and von Stechow *et al* 2015).

Model name	Model type	Metric for climate change mitigation costs	System boundaries	Non-climate sustainability objectives covered	References for model documentation
DNE21+	Energy system partial equilibrium model – intertemporal optimization	Energy system cost mark-up	Energy, climate	Air pollution, energy security	(Akimoto *et al* 2012, Sano *et al* 2015, 2012, Wada *et al* 2012)
GCAM		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, forestry, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, energy security	(Calvin *et al* 2016, 2013, 2009, Clarke *et al* 2007)
IMAGE	Energy system partial equilibrium model – recursive dynamic simulation	Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, biodiversity loss, energy security	(Bouwman *et al* 2006, Lucas *et al* 2013, van Ruijven *et al* 2012, van Vliet *et al* 2013)
POLES		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land use change	Air pollution, energy security	(Dowling and Russ 2012, Griffin *et al* 2013, IPTS 2010)
MESSAGE-MACRO	Systems engineering energy system model coupled with macroeconomic generable equilibrium model – perfect foresight, optimization	GDP & consumption loss, energy system cost mark-up, area under marginal abatement cost curve	Energy, aggregated representation of land-use GHG emissions, climate, water for energy	Energy access, water, air pollution/health, energy security	(McCollum *et al* 2013, Messner and Schrattenholzer 2000, Pachauri *et al* 2013, Rao and Riahi 2006, Riahi *et al* 2007)
REMIND	Optimal growth general equilibrium model – perfect foresight, optimization	Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate,	Air pollution, energy security	(Bauer *et al* 2011, Leimbach *et al* 2010, 2009, Luderer *et al* 2013a, 2011)
WITCH		Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate, climate damages and adaptation	Air pollution, energy security, adaptation	(Bosetti *et al* 2009b, 2006, DeCian *et al* 2011, Tavoni *et al* 2013)

6.8.2 Limitations of integrated models to address implications for non-climate sustainability objectives

In the WGIII AR5, alternative mitigation scenarios based on integrated models were mainly used to analyze (i) the technological and energy-system requirements of staying below a pre-determined GHG concentration threshold (such as decarbonization rates in a given period) and their regional interactions, (ii) the probability of exceeding that threshold, and (iii) the associated aggregate macroeconomic costs on global or regional levels (Bruckner *et al* 2014, Clarke *et al* 2014). Only a fraction of the studies that were assessed have also analyzed (i) the potential co-benefits for non-climate sustainability objectives (such as energy access, energy security and air quality) and (ii) the risks for non-climate sustainability objectives (such as land and water availability and biodiversity). But these studies either focused on specific co-benefits and SD risks or build on individual models (von Stechow *et al* 2015).

Similar to the challenges of aggregating local co-benefits on a global scale (von Stechow *et al* 2015), mitigation risks are challenging to quantify, let alone monetize, on a global level. Recently published literature hence focuses on technology-specific indicators for global mitigation risks, such as those associated with bioenergy (see, e.g. Bonsch *et al* 2016, Humpenöder *et al* 2014, Creutzig *et al* 2012b, 2012a), comparing scenario results with empirical evidence of energy technology transition processes in the past (e.g. Guivarch and Hallegatte 2013, Wilson *et al* 2013); or outlining the socioeconomic challenges of meeting international agreements given the discrepancy between current trends and long-term requirements (Luderer *et al* 2013b, Rogelj *et al* 2013a, 2013b, 2010, UNEP 2014, Luderer *et al* 2016, Kriegler *et al* 2015b, Rogelj *et al* 2015, Kriegler *et al* 2013).

Fully understanding the implications of alternative 2°C pathways for non-climate sustainability objectives would require modeling frameworks that can simultaneously optimize multiple objectives across sectors, regions and generations taking into account institutional settings. There are thus far, however, no modeling frameworks available that can optimize development pathways across that many objectives – also because the determination of damage functions is also highly value-laden (Ackerman and Heinzerling 2002, Lackey 2001, Pindyck 2013). This is why we draw on results from integrated models whose strength it is to analyze long-term mitigation pathways across sectors and regions in a consistent way although integrated models do neither optimize over other objectives nor measure the levels of sustainability objectives directly (for exceptions, see section 4 in von Stechow *et al* 2015). Hence, the interpretation of integrated model results as risk indicators for non-climate sustainability objectives provides, at best, a reasonable approximation of the interrelation between mitigation and multiple other objectives at the global level. Given the current little previous research on the impacts of climate change mitigation on non-climate sustainability objectives, this exercise already yields interesting new results.

Due to their global scope and coverage of the economy, energy, climate as well as land-use systems, integrated models inevitably are limited in the level of detail they can represent in other dimensions. For example, there is some critical literature on the implications of the structural set-up of and assumptions in integrated models for SD more broadly, such as for human development and inequality (e.g. Lamb and Rao 2015, Steckel *et al* 2013, Sathaye *et al* 2011, Stanton 2010). In the following paragraphs, we address some of these limitations to the extent they pertain to the models' ability to analyze the implications for non-climate sustainability objectives. Some of these limitations are briefly mentioned in the discussion of the main text while others are discussed in SI section 6.8.3. But rather than pointing to new insights, this section aims at providing an overview by structuring existing model critique into issues around (i) economic aggregation, (i) spatial aggregation, as well as (iii) institutional settings.

Like other economic models, integrated assessment models often assume homogeneity across economic agents by relying on a representative household rather than differentiating income groups or along other socio-economic criteria. This makes any analysis of distributional consequences within countries very challenging. Many climate policies have been identified as increasing equality challenges through, e.g. higher energy prices (see SI section 6.8.3.1.3), higher food prices (Wise *et al* 2014, Tadesse *et al* 2014, von Braun *et al* 2008) or indirectly through higher consumer prices (Fullerton and Metcalf 2001, Bovenberg and van der Ploeg 1994). However, integrated models can only take this into account if coupled to other models that consider, e.g. different income groups and/or rural and urban populations (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012) and skill levels (Guivarch *et al* 2011). Unless a model study is specifically designed to consider such distribution effects, multi-model results, such as those of AMPERE, are not suitable to analyze effects on SDG 1, 5 or 10.

Analyzing distributional effect among countries (SDG 10) is challenging due to the coarse spatial disaggregation of integrated models. The models only represent broad major economies, such as USA, China, Brazil and Japan as individual countries, while aggregating others to up to continental-scale macro-regions (Krey *et al* 2014). Analysis of distributional effects hence focuses on an inter-regional perspective and is only meaningful for alternative assumptions on international effort sharing regimes (Ekholm *et al* 2010, den Elzen *et al* 2008, den Elzen and Höhne 2008, Tavoni *et al* 2013, 2015, Aboumahboub *et al* 2014, Luderer *et al* 2012). In addition, models vary in their sectoral resolution, and only represent a limited number of sectors explicitly. This makes any analysis of technological issues related to spatial heterogeneity, such as infrastructure build-up and urban transformation (SDGs 9 and 11), highly challenging or even impossible.

With their focus on the technological and macroeconomic aspects of energy transitions, integrated models have very limited abilities to capture social phenomena and structural changes (Sathaye *et al* 2011). At the same time, there are many sustainability objectives for which institutional and social developments are much more decisive than the structure of the energy system, such as for the provision of basic services health, education and justice (SDGs 3, 4 and 16). This makes integrated models poorly equipped to address these SD dimensions.

Considering the models' limited ability to consider different income groups for different geographical characteristics and institutional settings, "an explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output" (Sathaye *et al* 2011, p 752). From the literature, we know, however, that there is a minimum energy requirement to satiate basic human needs (Pachauri and Spreng 2004, Steinberger and Roberts 2010, Lamb and Rao 2015) unless economic growth is assumed to break with historical trends (Steckel *et al* 2013). According to Lamb and Rao (2015), this threshold is approximately 30 GJ/year per capita. While the models typically do not explicitly take into account energy demands for basic needs related to cooking, heating, health and other infrastructure and services, their final energy pathways in mitigation scenarios still largely respect the 30 GJ/yr threshold. For instance, only two out of the seven models project final energy supply levels in mitigation pathways for India in 2050 that are below this level for reference assumptions on final energy (see Figure S-6.1). At the same time, as highlighted in the main text, the assumptions for lower energy demand growth need not additionally affect development outcomes but assume lower energy intensity (lowEI) through higher energy efficiency and, e.g. the viability of more compact, public transit-friendly urban areas (Riahi *et al* 2015).

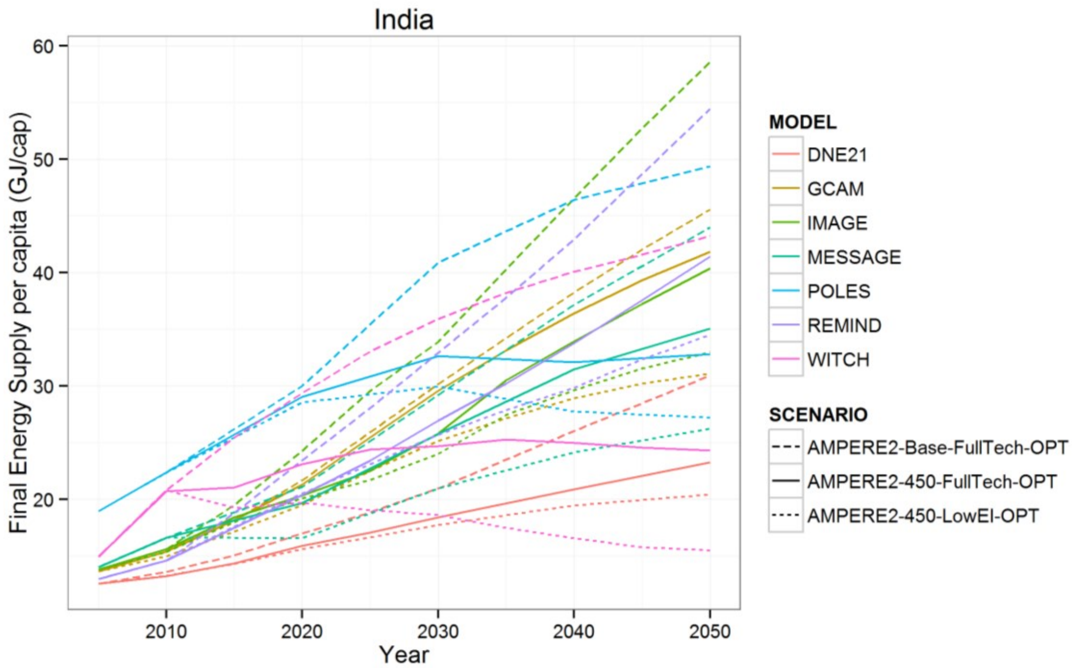

Figure S-6.1 Final Energy Supply (in GJ) per capita for baseline scenarios and 2°C pathways with conventional and low energy demand growth assumptions.

6.8.3 Linking energy-related SDGs and other sustainable energy objectives to SD risks and associated indicators based on integrated model results

This section gives some background on the choice of indicators calculated from model variables (column 1 in Table 6.2) that approximate SD risks (column 2) for energy-related SDGs and other sustainable energy objectives (column 3), used for the analysis of alternative 2°C pathways in the main text. The choice of SD risk dimensions discussed in this letter was guided by three criteria:

1. Discussion of risk dimensions and related quantitative indicators in the literature (see Table 6.1);
2. Possibility to link to energy-related SDGs (or other sustainable energy objectives) covering all three SD dimensions: economic, environmental and social (see SI section 6.8.3.1).
3. Public availability of model variables (from which suitable indicators can be calculated, see SI section 6.8.3.2) in the AMPERE database to serve transparency purposes (see SI section 6.8.4);

SI section 6.8.3.1 lays out in some detail the avenues by which mitigation can lead to increased or decreased risks for non-climate sustainability objectives and how the different SD risks can be linked to a set of energy-related SDGs and other sustainable energy objectives. It should be noted that many risk dimensions in fact have an impact on several SDGs – both in negative and in positive ways (see Figure S-6.2 for an overview) and choosing a single SDG to represent one risk dimension means simplifying these complex interlinkages. SI section 6.8.3.2 then explains how the chosen indicators for these risk dimensions can be calculated from integrated model variables reported in the AMPERE scenario database.

6.8.3.1 Linking SD risks to energy-related SDGs and other sustainable energy objectives

This section discusses the second criterion and reviews literature on the basis of which the link between SD risk dimensions and SDGs and other sustainable energy objectives can be established. This section is partly based on the Supplemental Material from von Stechow *et al* (2015) which reviews recent literature on the co-effects of mitigation measures in the energy supply as well as different energy demand sectors. As in von Stechow *et al* (2015), the discussion of co-effects in the agriculture, forestry and other land-use (AFOLU) sector is limited to the co-effects of increasing bioenergy supply – mainly because this was not a focus of the AMPERE project.

As discussed in SI section 6.8.2, integrated models have some limitations in their ability to address some non-climate sustainability objectives, such as distributional effects. This is why this section does not discuss links to some important SDGs, such as SDG1 ("end poverty in all its forms everywhere") and SDG 10 ("reduce inequality within and among countries"). To some extent, however, the chosen set of indicators implicitly speaks to the aims of poverty and inequality reduction, because:

i) food security concerns are most problematic for the urban poor (Ahmed *et al* 2009);

ii) air pollution disproportionally impacts the poor in dense urban areas (Frumkin 2002);

iii) not achieving energy access goals threatens the associated benefits in terms of local economic development, educational benefits, and income generation (SI section 6.8.3.1.6);

iv) economic growth reduction makes poverty reduction more challenging (SI section 6.8.3.1.4);

v) jobs at risk in the fossil fuel industry affect the unskilled most (Fankhauser *et al* 2008).

Bioenergy expansion and food security (SDG 2)

Achieving food security is an important aspect of SDG 2 but may be challenging to achieve in the light of climate change. On the one hand, stringent mitigation is likely to avoid the worst impacts of climate change which endangers sustainable food production systems (Porter *et al* 2014). On the other hand, an increased amount of biomass demand for energy purposes required in many mitigation scenarios may induce competition on arable land (except for bioenergy derived from residues, wastes or by-products) (Haberl *et al* 2014) with resulting impacts on food production and security (Ewing and Msangi 2009, Finco and Doppler 2010, Tilman *et al* 2009).[27] In a study that compares the effect of 100 EJ of lignocellulosic bioenergy to the potential climate impacts of a high-emission scenario on crop yields, the benefits of bioenergy for mitigation outweigh the adverse impacts in terms of food prices increases (Lotze-Campen *et al* 2014). But with higher amounts of bioenergy demand, the risks are likely to increase: Bioenergy production and the resulting land competition have implications for many non-climate sustainability objectives, such as reducing water availability (SDG 6.4), displacing communities and economic activities (SDG 8), driving deforestation (SDG 15.2), reducing soil quality (SDG 15.3), and impacting biodiversity (SDG 15.5) (Amigun *et al* 2011, Borzoni 2011, Chum *et al* 2011, Creutzig *et al* 2013, German and Schoneveld 2012, Hall *et al* 2009). Most integrated models are not yet well equipped to study these effects, but preliminary research exists, e.g. on water and biodiversity impacts (Bonsch *et al* 2016, De Fraiture *et al* 2008, PBL 2012, van Vuuren *et al* 2015). The main potential co-benefits seem to be related to improved access to energy services (SDG 7), job creation (SDG 8.3), and energy security (Amigun *et al* 2011, Arndt *et al* 2012, Duvenage *et al* 2012, Finco and Doppler 2010, Huang *et al* 2012, Leiby and Rubin 2013, Tilman *et al* 2009). More generally, due to the different bioenergy sources as well as to the specificities of the areas where bioenergy is produced, SD impacts from bioenergy are context-, pace- and size-specific (Bustamante *et al* 2014, Creutzig *et al* 2013, Popp *et al* 2011, Smith *et al* 2014b).

[27] Some agroforestry plantations can contribute to food security while producing biomass resources (Smith *et al* 2014b).

Air pollutant concentration and health via air quality (SDG 3.9)

One important aspect to ensure healthy lives is to substantially "reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination" (SDG 3.9). SO_2 and NOx, for instance, contribute to the acidification of water bodies (SDG 6.3) and soil (SDG 15.3) and NOx to eutrophication – a threat to biodiversity (SDG 15.5) (Hertwich *et al* 2010, Rockström *et al* 2009). Exposure to particulate matter (PM), emitted directly as BC and OC or formed from SO_2 and NOx, leads to premature deaths of more than 3.5 million people per year (Lim *et al* 2012, Smith *et al* 2014a). More than 80% of the global population is still exposed to PM concentrations that exceed the WHO recommendations of 10 µg/m3 $PM_{2.5}$ (Rao *et al* 2013). But the local health effects can differ substantially depending, for example, on the efficiency of the combustion process, the place of the emission source, the scrubber technology, the downwind population concentration as well as the background pollution from other sources (Bell *et al* 2008, Smith and Haigler 2008, Sathaye *et al* 2011).

In addition to the reduced health effects of less air pollution and resulting water and soil pollution, reducing air pollutant emissions arising from energy supply also helps protecting and restoring the sustainable use of marine and terrestrial ecosystems (SDGs 14 and 15). Even though some individual low-carbon energy technologies such as concentrated solar power tower technologies, some hydropower plants and CCS technologies show considerable pollution-related health and ecological effects – taking into account life-cycle emissions and thus accounting for emissions from material and fuel production, manufacturing, operation and decommissioning – Hertwich *et al* (2015) generally found significantly lower pollution-related indicators for renewable energy (RE) technologies (see discussion in SI section 6.8.3.1.6 on wind energy and PV). This co-benefit is mainly due to the reduction of co-emitted pollutants associated with the decarbonization of energy supply, which is nearly complete in 2050 for stringent 2°C pathways (Bruckner *et al* 2014, Clarke *et al* 2014, Riahi *et al* 2015). Integrated model studies indicate that there are significant co-benefits for a number of pollutants – up to 50/35/30/22% reductions by 2030 globally of SO_2, NOx, $PM_{2.5}$, and Hg emissions or concentrations relative to baseline scenarios (see von Stechow *et al* 2015 for a review).

Finally, methane emissions that contribute to the formation of tropospheric ozone with negative impact on crop yields (van Dingenen *et al* 2009) can be reduced in coal mining and gas and oil production (Bruckner *et al* 2014). Reducing fossil fuel use, particularly coal, and methane leakage reduction can mitigate near-term climate change and improve health and food security (Anenberg *et al* 2012, Shindell *et al* 2012).

Energy price growth and energy access (SDG 7)

SDG 7 aims at ensuring "universal access to affordable, reliable, and modern energy for all". This is a huge challenge since more than 1.3 billion people worldwide, especially in sub-Saharan Africa and developing Asia, lack access to electricity and over 2.5 to 3 million people are estimated to lack modern fuels for heating and cooking (IEA 2012, Pachauri *et al* 2013). Whilst improvements in energy access do not need to entail significant changes in GHG emissions (Pachauri *et al* 2013), climate policies are likely to increase energy prices, at least in the short term, due to carbon pricing, fuel switching and higher energy production costs from low-carbon energy technologies (Bertram *et al* 2015b, Bruckner *et al* 2014, Fischedick *et al* 2011, Jakob and Steckel 2014) which can result in higher challenges for achieving energy access objectives (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012, van Vuuren *et al* 2015).

Even though the global energy price index that was used for this letter (see SI section 6.8.3.2.2) is generally set to increase in mitigation scenarios with conventional energy demand growth assumptions, the effect on those without energy access today depends importantly on locally specific circumstances, such as the type of fuel used by different income groups, the distribution of the revenues from climate policy and the effectiveness of pro-poor policies that are in place today or could be implemented to complement climate policies (Casillas and Kammen 2010). In fact, a recent study shows that the costs of achieving energy access change with the stringency of climate policy but are even more sensitive to the way energy access policies are implemented (Cameron *et al* 2016).

The effects of energy prices on economic growth are not explicitly analyzed here because the macroeconomic effects of mitigation, including general equilibrium effects of changing energy prices, are captured to some extent by the integrated models (see below in SI section 6.8.3.1.4). To what extent higher energy prices are a concern from an inequality perspective depends on the distributional consequences, which cannot be derived from the AMPERE scenario database (see SI section 6.8.2). Since poorer households spend a higher proportion of their disposable income on energy needs, higher energy prices are a problem not just for those without sufficient energy access today (Moore 2012). While there is a regressive impact of higher energy prices in developed countries (Grainger and Kolstad 2010, Romero-Jordán *et al* 2016, Frondel *et al* 2015, Nelson *et al* 2011), the empirical evidence is mixed for developing countries (Jakob and Steckel 2014). Fuel taxes, for example, seem to be generally progressive in poor countries (Somanathan *et al* 2014).

In addition, higher energy prices are not only a concern for energy access goals but also for health (SDG 3): Higher energy prices could adversely affect the ability of households to guarantee a certain level of consumption of domestic energy services (especially heating) or may place disproportionate expenditure burdens to meet these needs. Fuel poverty has a range of negative effects on the health and welfare of fuel poor households, such as an increase in excess winter mortality rates, excess morbidity effects, depression and anxiety (Clinch and Healy 2001). But these effects can be greatly reduced by mitigation measures in the buildings sector (Ürge-Vorsatz and Tirado Herrero 2012).

Consumption growth reduction and economic growth (SDG 8.1)

Sustaining economic growth is one of the core requirements to achieve a number of non-climate sustainability objectives, such as poverty reduction (Ravallion and Chen 1997, Rodrik 2008) and higher employment levels (Blanchard and Wolfers 2000, Crivelli *et al* 2012, McMillan *et al* 2014), and are reflected in SDGs 1 and 8. While the negative impact of stringent climate policy on aggregate measures of consumption growth is limited (see SI section 6.8.3.2.1), integrated models project higher transitional economic growth reductions in the decade after implementation of the climate policy (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013b, 2016). Because the effects in the short to medium term are of particular interest for achieving SDG 8.1, this letter's focus is on transitional rather than aggregate long-term metrics of economic growth reductions as mitigation risk indicator.

Stranded fossil investment and full employment (SDG 8.3)

Achieving full and productive employment features as another sub-goal of SDG 8. While many mitigation measures potentially have a positive effect on gross job creation (such as energy efficiency measures in the housing and industry sectors as well as upscaling of RE, see below in SI section 6.8.3.1.6), the net effect of mitigation pathways on employment in the medium to long term remains disputed, considering all aspects of mitigation technologies (e.g. labour intensity and implications for job quality and skills) as well as trade, investment, innovation and general equilibrium effects (Babiker and Eckaus 2007, Böhringer *et al* 2013, Clarke *et al* 2014, Fankhauser *et al* 2008, Guivarch *et al* 2011). Yet, it is clear that many jobs in the fossil fuel industry (and the associated value chains) will be lost in the short term due to the energy system transition from carbon-intensive industries towards more low-carbon sectors (Fankhauser *et al* 2008).

Since it is difficult for policy makers to credibly commit to a climate policy trajectory, investors will find it challenging to make investment decisions consistent with long-term climate goals in a changing policy environment dominated by uncertainties about the possibility and extent of global cooperation on climate change mitigation (Brunner *et al* 2012). Accordingly, from 2005 through 2013, approximately 722 GW of new capacity was added to the global coal fleet and over 1,000 GW of coal power plant capacity is still proposed globally – despite a drop of 23% from 2012 numbers (Shearer *et al* 2015). Some experts speak about a 'renaissance of coal' (Steckel *et al* 2015). To avoid excess job losses (and the associated negative effects on overall economic output) when choosing climate policies, decision makers should be interested in minimizing the additional build-up of long-lived carbon-intensive infrastructure (such as coal power, see SI section 6.8.3.2) (Rozenberg *et al* 2014). This is because a large share of any new coal capacity built over the next decades would likely need to retire early to comply with the carbon budget consistent with the 2°C target – with the associated employment implications.[28] This is particularly important in emerging economies where most new capacity would be built (Bertram *et al* 2015a, Johnson *et al* 2015). Early retirement of thermal power plants also impacts power grid stability (Holttinen 2012) that is discussed in the next sub-section.

[28] As witnessed in Germany, even the prospect of climate regulation that would necessitate the retirement of rather old coal power plants led to a public debate and subsequent withdrawal of the initial proposal, based on (mainly unsubstantiated) arguments around potentially substantial job losses in particular regions and supplying industry (Oei *et al* 2015).

Wind & PV grid integration and resilient infrastructure (SDG 9)

Building resilient infrastructure features as SDG 9 to support economic development and human well-being. As described in SI section 6.8.3.2.7, adding large amounts of partially dispatchable and predictable RE capacity (e.g. wind energy and PV) in a short time is a challenge for power grids. The resulting technical and economic risks may even put public acceptance of RE at risk as can be observed in the public debate on the German 'Energiewende' (Frondel *et al* 2015, 2012). This is a concern from the perspective of many other SDGs on which higher RE deployment would have positive impacts:

- Replacing coal with wind and PV would be associated with a wide range of co-benefits as their pollution-related indicators are generally significantly lower (Hertwich *et al* 2015).[29] This would reduce the number of deaths and illnesses from air pollution (SDG 3.9), improve the water quality by reducing pollution (SDG 6.3) and contribute to "conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services" (SDG 15.1). This is also helped by the fact that the consumptive water use of wind energy and PV is small (Meldrum *et al* 2013).
- Higher deployment of wind energy and PV links directly to a sub-goal of SDG 7 (7.2: "increase substantially the share of RE in the global energy mix by 2030") because they can help promote off-grid access to energy services in countries with little central grid access. This is because research indicates that improved energy access by means of RE also stimulated local economic development in a number of developing countries (Goldemberg *et al* 2008, Walter *et al* 2011) and led to educational benefits and enhanced support for income generation in large parts of the developing world (Bazilian *et al* 2012, Kanagawa and Nakata 2007, Sokona *et al* 2012).
- Studies from China, Germany, Spain and the US found net job gains due to an increased share of RE with higher labour intensity (Cai *et al* 2011, Lehr *et al* 2012, Ruiz Romero *et al* 2012, Wei *et al* 2010). Similar results have been found for RE in the buildings sector (Lucon *et al* 2014). On the one hand, this may help achieving SDG 8, namely "higher levels of productivity of economies…through a focus on high value added and labour-intensive sectors" (SDG 8.3). On the other hand, RE, particularly PV, still relies on substantial public support, implying that some of the above adverse effects apply with respect to opportunity costs of using public funds and skilled workers as well as trade and general equilibrium effects (see SI section 6.8.3.1.5) (Böhringer *et al* 2013, Frondel *et al* 2010, Lambert and Silva 2012).
- Finally, higher RE deployment in mitigation scenarios generally leads to lower energy imports (Criqui and Mima 2012, Jewell *et al* 2014, Kruyt *et al* 2009), a co-benefit for energy security.

[29] It should be noted, however, that collisions of birds and bats with wind power plants are an important concern (Giavi *et al* 2014, Lehnert *et al* 2014, Marques *et al* 2014).

Energy security

Energy security vulnerabilities can be characterized by three different perspectives: sovereignty (risks primarily arise from foreign actors), robustness (risks can be calculated and avoided) and resilience (risks are uncertain and systems must be designed to be able to recover from disruptions) (Cherp and Jewell 2014, 2011). For the purposes of this letter, we focus on oil security since it is the most vulnerable fuel globally with most countries dependent on imported oil from a limited number of exporting countries, the most acute scarcity concerns (both real and perceived) and it faces virtually no substitutes in the transport sector (Cherp *et al* 2012). In fact, the inflexibility of the oil system is one of the reasons it has been one of the main foci of energy security strategies, in particular with the creation of the International Energy Agency (IEA) after the 1970s oil crises.

For our analysis, we consider one indicator for each perspective on oil security: cumulative oil trade to represent sovereignty risks (see SI section 6.8.3.2.10); cumulative oil extraction to represent robustness concerns (see SI section 6.8.3.2.11); and non-oil use in the transport sector to represent the resilience perspective (see SI section 6.8.3.2.12). This admittedly neglects energy security risks arising from critical infrastructure vulnerabilities (Farrell *et al* 2004) – except short-term reliability concerns from variable renewables (see SI section 6.8.3.2.7) (Johansson 2013) – but infrastructure is not very well depicted in integrated models so is not the best tool to explore these types of risks (see SI section 6.8.2).

Peaceful use of nuclear power

Many mitigation scenarios depict tremendous growth in nuclear energy – up to four times current levels by mid-century (Kim *et al* 2014). The risks associated with nuclear energy include accidents, physical security – nuclear materials falling into the wrong hands – and proliferation – the spread of nuclear weapons and fissile material to new countries (von Hippel *et al* 2012).[30] Similar to the relationship with energy intensity (EI), the less energy produced from nuclear, the lower each of these risks is. The accident risk is calculated in terms of incidents per reactor years; thus all else being equal, increasing the nuclear power fleet increases the risk of accidents. Yet, many integrated models do not distinguish between types of nuclear power plants, let alone which safety mechanisms are implemented where so the only way to analyze this would be assume the same accident risk for the full nuclear fleet. Thus for the purposes of our analysis we focus on physical security and proliferation risks related to nuclear power (see SI section 6.8.3.2.5).

Environmental risks of CCS chain and sustainable production (SDG 12.4)

Achieving environmentally sound management of chemicals and reducing their release to air and water to minimize their adverse impacts on human health and the environment features prominently in SDG 12. While CCS is an important mitigation

[30] Some epidemiological studies on the health effect of radioactive material handling find a higher childhood leukemia of populations living within 5 km of nuclear power plants (Heinävaara *et al* 2010, Kaatsch *et al* 2008, Sermage-Faure *et al* 2012). Nuclear energy also reduces pollution-related indicators compared to coal with positive health effects (Hertwich *et al* 2015) making the net effect on health very challenging to assess.

technology, particularly because it can be coupled with bioenergy to produce negative emissions and thus increases the flexibility to reach stringent climate goals (Clarke *et al* 2014, Fuss *et al* 2014), high deployment of CCS increase the environmental concerns of fossil-fuel based power supply. On the one hand, the CCS process requires 16-44% of additional energy (Corsten *et al* 2013), thereby increasing the fuel requirements and associated environmental impacts, such as ecological damage (SDG 15), higher mudslides risks, and water contamination (SDG 6.3) (Adibee *et al* 2013, Palmer *et al* 2010, Smith *et al* 2013). On the other hand, CO_2 capture requires a pure gas stream, reducing some air pollution from the power plant, such as SO_2 (Koornneef *et al* 2008). Investigating different CCS technologies for relevant life-cycle indicators, Hertwich *et al* (2015) find that, on balance, CCS leads to increases in PM, toxicity and eutrophication by 5-60% compared to modern coal and gas power plants. Many of these additional air pollutant emissions would also negatively impact health (SDG 3.9, see SI section 6.8.3.1.2) and marine ecosystems (SDG 14). If coal is substituted by biomass (to enable net negative GHG emissions via BECCS), Schakel *et al* (2014) find that the biomass supply chain and the combustion-related pollution are comparable to that of coal with respect to environmental and health impacts.

Most CCS technologies also significantly increase water withdrawal and consumption (up to 100%) due to efficiency penalties and additional process demands (Zhai *et al* 2011, Meldrum *et al* 2013) – with the latter causing ecological impacts (Verones *et al* 2010). There are also concerns about groundwater contamination due to CO_2 leakage (Apps *et al* 2010, Atchley *et al* 2013, Siirila *et al* 2012). As much as additional wind energy and PV helps alleviating concerns about water availability and quality, CCS may hence add to these (SDG 6.3). As discussed in SI section 6.8.3.2.4, there are substantial uncertainties attached to the hydrogeological characteristics and volumes of the geological reservoirs. For example, concerns about induced seismicity could potentially affect surface structures or simply alarm the population (Mazzoldi *et al* 2012). With open questions about the resilience of existing reservoirs (White *et al* 2014), higher CCS deployment may increase concerns about the resilience of the installed infrastructure (SDG 9).

On the positive side, retrofitting CCS can potentially alleviate the extent of stranded investment of coal-power plants (Johnson *et al* 2015). Successful deployment of CCS technologies could potentially preserve many jobs in the fossil-fuel industry (Fankhauser *et al* 2008, Wei *et al* 2010) – a contribution to achieving SDG 8.3 in the short term.

Peak atmospheric CO_2 concentration and minimization of ocean acidification (SDG 14.3)

Ocean acidification is an important global change problem and hence features as one sub-goal of SDG 14. While it is often analyzed together with impacts of climate change (IPCC 2014), future changes in ocean acidification are largely independent of the amounts of climate change but are mainly driven by CO_2 emissions (Cao *et al* 2007). As such, reductions in ocean acidification and associated aragonite saturation states (Ω_a) can also be regarded as a co-benefit of CO_2 emissions reductions primarily targeted at climate change mitigation (Joos *et al* 2011). High changes in pH and Ω_a adversely affect vulnerable marine organisms that build shells and other structures from aragonite (Orr *et al* 2005). For example, if atmospheric CO_2 is stabilized at 450 ppm, only 8% of existing coral reefs will be surrounded by water with pre-industrial saturation levels down from 98% (Cao and Caldeira 2008). These concentrations are surpassed by 2050 in some delayed 2°C pathways due to high concentration overshoot whereas pathways without negative emissions stay below that threshold. Whereas global mean temperature change mainly depends on cumulative CO_2 emissions (IPCC 2014), the response of pH and Ω_a is delayed in the ocean interior – highlighting the importance of 2°C pathways with low concentration overshoot to avoid irreversible damage (Mathesius *et al* 2015).

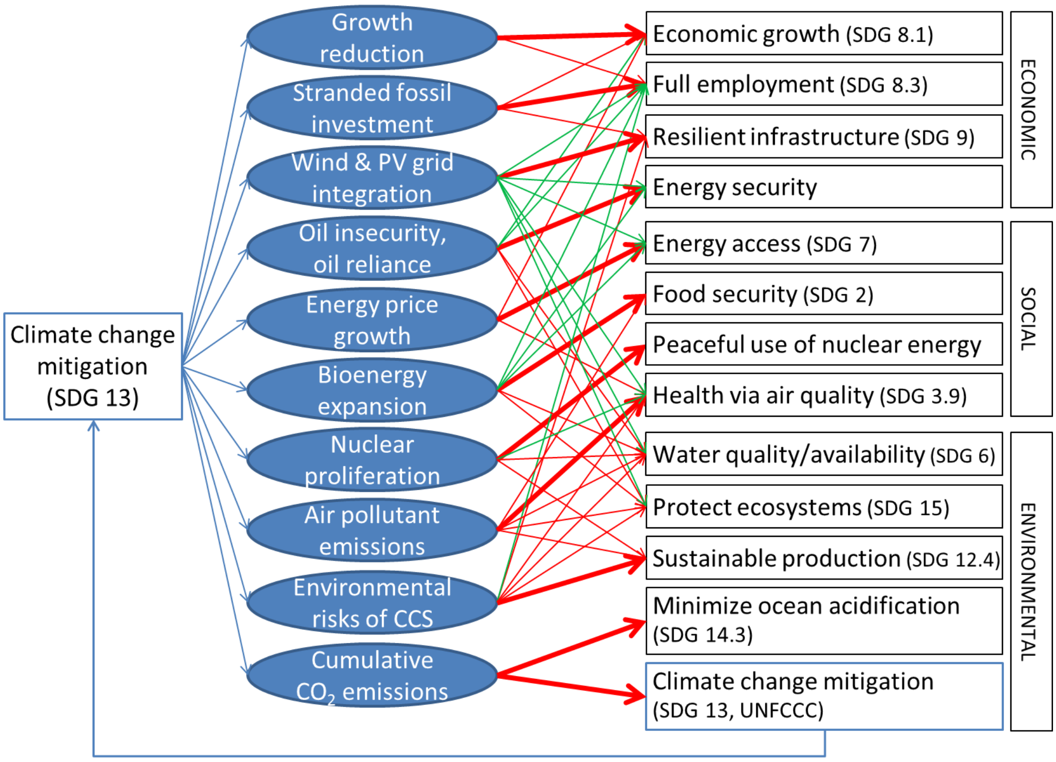

Figure S-6.2 The SD risks were chosen (i) based on existing literature and such that (ii) associated indicators can be calculated from integrated model variables that are readily available from scenario results in the AMPERE scenario database to serve transparency purposes; and (iii) link directly to a set of energy-related SDGs and other multilaterally agreed sustainable energy objectives covering all three SD dimensions: economic, environmental and social.

6.8.3.2 Linking indicators calculated from integrated model variables to SD risks

All indicators for SD risks that are described in detail below – following the order of the indicators as they appear in Figure 6.5 – show the difference between the value for each mitigation scenario and that for the baseline as a percentage of the baseline value (except for Figure 6.5 which compares alternative 2°C pathways to each other, see Table S-6.4 for the underlying data). The baseline is derived from the values of the "AMPERE2-Base-FullTech-OPT" scenario in the same model, unless otherwise stated. For the indicator for which baseline scenarios show values of or near zero (and hence does not lend itself to an analysis of relative changes), the following paragraphs introduce a reference value against which the values from mitigation scenarios are compared (see SI section 6.8.3.2.4).

Maximum decadal consumption growth reduction

While cost-benefit analyses (CBA) of climate change mitigation has been prominently discussed in climate economics (Stern, 2008), the approach has many drawbacks (as discussed, e.g. in Edenhofer *et al* 2014, Kunreuther *et al* 2014, Pindyck 2013). Most studies with integrated models rather analyze the macroeconomic costs of not exceeding a specific mitigation goal in the most cost-effective way (CEA, see SI section 6.8.1).

Since in this mode of operation mitigation scenarios do not account for avoided damages or co-benefits, the climate constraint to the respective optimization models leads to lower economic activity and hence a reduction of available consumption compared to baseline developments (Paltsev and Capros 2013). Depending on the modeling framework, these effects are measured in different metrics, such as the area under the marginal abatement curve, the aggregated and discounted increase in energy system costs, or aggregated and discounted GDP or consumption losses relative to GDP (see Table S-6.1). While many studies have analyzed aggregate economic indicators for the mitigation costs, the analysis of delayed scenarios highlights that such cumulative metrics are not reflecting the full economic costs borne by societies: due to the discounting usually applied when calculating aggregated costs, sharp increases of costs in later decades (due to delayed climate policy scenarios) are not fully reflected in cumulative metrics. Metrics that measure transitional costs, such as the maximum transitional costs to be born within a decade, expressed as reduction of consumption growth, have been used to illustrate the economic challenges beyond the cumulative, discounted approach (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013b) and can be calculated based on reported data from MESSAGE, GCAM and WITCH.

For the purpose of this letter, the indicator is defined as the maximum difference (in percentage change) in the consumption (C) growth rate (g) over a decade between mitigation and baseline scenarios in the same model – compared to a 1% change in the growth rate in the same period.

$$\max_{2010<t<2050}\left(g^{\mathrm{Baseline}}(t)-g^{\mathrm{Mitigation}}(t)\right)/1\%$$

where for each scenario

$$g(t)=\frac{C(t)-C(t-10)}{C(t-10)}\cdot 100\%$$

is the decadal rate of growth (in percentage change) for each scenario.

Maximum decadal energy price growth

Measuring the macroeconomic costs of mitigation for societies implicitly or explicitly takes into account inter-generational distributions by means of choosing a specific discount factor. But adjustment costs and intra-generational distribution issues are often neglected (Fleurbaey *et al* 2014, Fleurbaey and Zuber 2012). While direct analysis of the distributional impacts of climate policy is not possible with such global models with only coarse geographical scales and assumptions on homogeneity of economic agents (see SI section 6.8.2), some recent studies identified economic indicators that could be indirectly related to distributional issues. One example for such an indicator is the maximum growth of an energy price index to be born within a decade, calculated similarly to a consumer price index, due to climate policies (Bertram *et al* 2015b, Luderer *et al* 2013b). Although such an indicator is only an approximation for the actual increase of household expenditure for energy services (see SI section 6.8.3.1.3), it is an interesting alternative, given that energy services are not explicitly modeled in the majority of integrated models. Since the models that report secondary energy prices (MESSAGE and REMIND) include carbon price mark-ups, the indicator is set to increase for climate policy.

For the purpose of this letter, the indicator is defined as the maximum decadal increase in the Energy Price Index (*EPX*) in the given time period, where *EPX* is the weighted average of the price (*p*) of the secondary energy demand basket (*SE*) relative to the price of the same basket 10 years previously.

$$EPX(t) = \sum_i p_i(t) SE_i(t) \,/ \sum_i p_i(t-10) SE_i(t),$$

such that maximum decadal energy price growth (in percentage change) is

$$\max_{2010<t<2050} \frac{EPX_{\text{Mitigation}}(t) - EPX_{\text{Baseline}}(t)}{EPX_{\text{Baseline}}(t)} \cdot 100\%$$

Idle coal capacity per year

Due to the high GHG emissions of the current, mainly fossil-based, energy system, stringent mitigation goals necessarily lead to a significant energy system transition (Bruckner *et al* 2014). Should the global community or individual countries ramp up climate policies, some existing and even newly built fossil capacities may turn out to be unprofitable since they are not able to recover their short-term costs, ending up as stranded investments (Bosetti *et al* 2009a) (see SI section 6.8.3.1.5).

Since integrated models project more carbon-intensive coal power plant build-up for the next decades in delayed mitigation pathways (assuming myopic investment behavior), these are the plants that would – under normal market conditions – still operate in 2050 but may have to be prematurely retired for suddenly high carbon prices after the period of delay (Bertram *et al* 2015a, Johnson *et al* 2015). This is approximated by the amount of ‘idle coal capacity’ in the models which depends on the carbon intensity reduction rates necessary to stay within the carbon budget which is more challenging the later emissions peak and the higher this peak level will be (Johnson *et al* 2015). Here, we build on the metric used by Bertram *et al* (2015a), who calculate the average load factor of the global coal capacity, albeit looking at the share lying idle in mitigation scenarios.

For the purpose of this letter, the indicator measures the percentage change in the share of coal power plant capacity – "Capacity|Electricity|Coal|w/o CCS" (*Capacity_Coal* in GW) – in 2050 that is not being used to generate electricity – "Secondary Energy|Electricity|Coal|w/o CCS" (*SE_Coal* in EJ/a) – i.e. is lying idle:

$$\frac{\left(1-\frac{Capacity\_Coal^{\mathrm{Mitigation}}(2050)}{SE\_Coal^{\mathrm{Mitigation}}(2050)\cdot \mathrm{s/a}}\right)-\left(1-\frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050)\cdot \mathrm{s/a}}\right)}{\left(1-\frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050)\cdot 0.031536}\right)}\cdot 100\%$$

CO_2 captured and stored per year

In addition to other concerns (see SI section 6.8.3.1.9), one major uncertainty in the process chain of CCS are the hydrogeological characteristics and volumes of the geological reservoirs in which the CO_2 is supposed to be stored (Humpenöder *et al* 2014). Since the global storage potential of deep saline aquifers is large compared to alternative storage types (1000 up to 10000 Gt, see Benson *et al* 2005), the uncertainty about hydrogeological data leads to high ranges of estimates. The IEA qualifies the storage in depleted oil and gas fields for which reliable data already available as well as the usage of CO_2 for 'Enhance Oil Recovery (EOR)' as 'early opportunities' (IEA 2009). Since point sources of CO_2 do not necessarily arise in places with the largest storage sites, source-sink matching leads to lower storage potential estimates. If global CO_2 storage demand exceeds these estimates, more risky reservoir types have to be tapped.

Drawing on the regionally differentiated estimates of Hendriks *et al* (2004), the global CO_2 storage potential for depleted oil and gas fields stands at 250 Gt CO_2 (best estimate). Assuming an injection duration of 50 years (to avoid pressure build-up, see Szulczewski *et al* 2012), the storage potential per year amounts to 5 Gt. Although more storage volume is available from other reservoir types (deep saline aquifers, coalbed methane recovery), all values above 5 Gt are judged as more risky.

For the purpose of this letter, the indicator measures the percentage increase of CO_2 emissions stored – "Emissions|CO2|Carbon Capture and Storage" (*Emi_CCS*) – in geological storage facilities in 2050 relative to a reference value of 5000 Mt that can presumably be stored at low technical risks.

$$\frac{Emi_{\mathrm{CCS}^{\mathrm{Mitigation}}(2050)}-5000\ \mathrm{Mt\ CO_2}}{5000\ \mathrm{Mt\ CO_2}}\cdot 100\%$$

Nuclear capacity expansion in Newcomer countries

Today, only thirty countries have nuclear energy but much of the development of nuclear power in low-carbon scenarios happens in regions where nuclear power has played a very small role. The question then becomes, does a spread of nuclear power increase the risk of proliferation and physical security concerns? The relationship between proliferation and civilian nuclear power programs is contentious to say the least. However, there is generally consensus that civilian nuclear power programs shorten the time it would take a country to develop the bomb (Sagan 2011). There's also empirical evidence that 'client' countries that have nuclear cooperation agreements with 'supplier' countries are more likely to develop nuclear weapons (Fuhrmann 2009). Since few 'Nuclear Newcomers' would be able to introduce nuclear power without significant international support (Jewell 2011), the growth of nuclear proliferation would increase with the spread of the technology to new countries.

To measure this risk, we developed an indicator for the (percentage) change in the capacity of nuclear power in countries which today do not currently have nuclear power. In the absence of country-by-country values, this is approximated as the sum of nuclear capacity – "Capacity|Electricity|Nuclear" (*Capacity_Nuc*) – in 2050 in regions (*r*) that largely do not have nuclear power (Asia, the Middle East and Africa and Latin America) less the sum of the projected nuclear capacity (*i*) in those countries which do (China, India and Brazil) and for which the AMPERE database supplies data.[31]

$$\frac{NewNuclear^{\mathrm{Migitation}} - NewNuclear^{\mathrm{Baseline}}}{NewNuclear^{\mathrm{Baseline}}} \cdot 100\%,$$

where

$$NewNuclear = \sum_{r} Capacity\_Nuc(2050) - \sum_{i} Capacity\_Nuc(2050)$$

Biomass supply for energy per year

Biomass is a basic resource for food, fodder and fibre and is hence crucial to many peoples' well-being, particularly for those that have to rely on subsistence agriculture and on traditional biomass for cooking and heating. Since it is also a versatile form of RE, potentially being able to be converted to liquid and gaseous fuels, electricity and heat, it also plays an important role in integrated model projections of energy systems moving away from fossil-based fuels (Chum *et al* 2011, Smith *et al* 2014b). For many technological routes, this implies that bioenergy may compete with other biomass demand for arable land (Haberl *et al* 2014). Since land is a finite resource, this could lead to a range of effects for SD (see SI section 6.8.3.1.1).

Since there are many uncertainties involved in calculating the land use impact of bioenergy, including the (induced) yield changes through agricultural technology innovation and diffusion processes and the interactions with dietary patterns and non-climate policies (Creutzig *et al* 2012a, PBL 2012, Popp *et al* 2014, Rose *et al* 2012, Sathaye *et al* 2011, Smith *et al* 2014b, Wise *et al* 2009), we simply use the total amount of bioenergy as an imperfect but available indicator for this range of potential risks. For the purpose of this letter, the indicator refers to the percentage change in the primary energy supply of biomass – "Primary Energy|Biomass" (*Bioenergy*) – in 2050 relative to the baseline scenario.

$$\frac{Bioenergy^{\mathrm{Mitigation}}(2050) - Bioenergy^{\mathrm{Baseline}}(2050)}{Bioenergy^{\mathrm{Baseline}}(2050)} \cdot 100\%$$

[31] Although South Korea (21.6GW) and South Africa (1.8GW) already have nuclear capacity (whose lifetime ends, however, before 2050), the AMPERE database does not report country-specific data in these cases. This likely implies a slight overestimation of the nuclear newcomers capacity – in baseline and mitigation scenarios.

Maximum decadal PV and wind capacity upscaling

Modern electrical power systems widely differ in terms of their development and reliability across countries. But the balancing of electricity supply and demand requires complex operational planning from the management of instantaneous changes in demand to the longer-term investment decisions in generation capacity and transmission grids. Because the generators, interconnectors and loads are designed to operate within certain frequency limits, large amounts of only partially dispatchable and predictable power capacity are potentially a threat to the security and reliability of the system. This entails the need to build new grid infrastructure (e.g. grid reinforcements and new lines) both inside the region as well as interconnection to neighbouring regions. But because the construction of networks involves long lead times, "… major investments will be needed and will need to be undertaken in such a way, and far enough in advance, so as to not jeopardize the reliability and security of electricity supply (Sims *et al* 2011, p 627)."

With timing conflicts (PV and wind plants can be constructed in less than 2 years, while planning, permitting and constructing a transmission line takes 5 to 10 years) and cost recovery uncertainties, very fast upscaling of PV and wind power plants is a risk – both technically and economically (Sims *et al* 2011). Possible other solutions (such as curtailment, provision of ancillary services, demand-side measures and additional reserve capacity and storage facilities) may have to be relied on for higher penetration rates but also requires additional time and/or investments (Hirth 2013, Hirth and Ueckerdt 2013, Holttinen *et al* 2011, Söder *et al* 2007, Ueckerdt *et al* 2013). Because the majority of integrated models only report the various variables in 10-year time steps, we have to rely on decadal values for upscaling that we use as a mitigation risk indicator reflecting both technical and economic risks.

For the purpose of this letter the indicator refers to the maximum decadal increase (in percentage change) in the combined capacity of PV and wind power – "Capacity|Electricity|Solar|PV" (*Capacity_PV*) and "Capacity|Electricity|Wind" (*Capacity_Wind*) – between 2010 and 2050 relative to the maximum decadal increase in capacity in baseline scenarios.

$$\frac{CapacityUpscaling^{\mathrm{Migitation}}(t) - CapacityUpscaling^{\mathrm{Baseline}}(t)}{CapacityUpscaling^{\mathrm{Baseline}}(\mathrm{t})} \cdot 100\%,$$

where

$$CapacityUpscaling = \max_{2010<t<2050} Capacity\_PV(t) + Capacity\_Wind(t)$$

Cumulative CO_2 emissions

As described in SI section 6.8.1, the emission pathways in integrated model mitigation scenarios are designed to meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. They are, however, given the flexibility to overshoot the constraint over the course of the century. Otherwise, many models would not find a solution for mitigation scenarios with very low concentration targets. This implies that CO_2 emission trajectories and concentrations can differ substantially across alternative 2°C pathways –

mainly depending on the deployment levels of negative emission technologies in the second half of the century (Clarke *et al* 2014, Fuss *et al* 2014). As described in SI section 6.8.3.1.10, this can have very different implications for the marine environment, because past CO_2 emissions can leave a substantial legacy in the marine environment due to delayed responses in the ocean interior and irreversibility of some of the impacts of ocean acidification, such as calcification (Boucher *et al* 2012, Zickfeld *et al* 2012). We hence look at differences in cumulative CO_2 emissions by 2050 in alternative 2°C pathways to approximate the changes is risks due to ocean acidification and its implication for marine ecosystems.

For the purpose of this letter, the indicator refers to the percentage change in cumulative CO_2 emissions – “Emissions|CO2” (*Emi_CO2*) – from 2020-2050.

$$\frac{Emi\_CO2^{\text{Mitigation}} - Emi\_CO2^{\text{Baseline}}}{Emi\_CO2^{\text{Baseline}}} \cdot 100\%$$

Cumulative values are calculated by multiplying the value in each timestep (*t*) by half the difference between that timestep's year (*Y*) and the previous timestep's year plus half the difference between its year and the next timestep's year, for all timesteps included in the period under consideration.

Cumulative SO_2 and BC emissions

The emissions arising from the combustion of fossil fuels, such as soot (black carbon, BC), sulfur dioxide (SO_2), nitrogen oxides (NOx) and mercury (Hg), cause significant and widespread human health impacts as well as ecological impacts as described in SI section 6.8.3.1.2. Although the negative environmental and health impacts primarily arise from the (regionally very different) concentration of these pollutants, the scenario databases merely report the amount of global emissions that serve here as indicator. There are, however, individual studies that establish a clear link between emissions, concentrations and the negative impacts of the pollutants in question (Rao *et al* 2013, Shindell *et al* 2012, Smith and Mizrahi 2013).

For the purpose of this letter, the indicator for cumulative BC Emissions (2020-2050) refers to the percentage change in the cumulative value of BC emissions – "Emissions|BC" (*Emi_BC*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_BC^{\text{Mitigation}} - Emi\_BC^{\text{Baseline}}}{Emi\_BC^{\text{Baseline}}} \cdot 100\%$$

For the purpose of this letter, the indicator for cumulative SO_2 Emissions (2020-2050) refers to the percentage change in the cumulative value of sulfur emissions – "Emissions|Sulfur" (*Emi_SO2*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_SO2^{\text{Mitigation}} - \text{Emi}\_SO2^{\text{Baseline}}}{Emi\_SO2^{\text{Baseline}}} \cdot 100\%$$

Cumulative global oil trade

For oil trade, we measure interregional oil trade as an indicator for the concerns around the sovereignty perspective that sees the origin of risks in deliberate actions of foreign actors (Jewell *et al* 2014). While this indicator does capture lower risks from decreasing oil imports, it also measures lost oil export revenues for oil exporters, which is most likely a loss rather than a benefit for major oil exporting countries which would lose oil export revenues from a fall of oil trade (Clarke *et al* 2014).

With increasing ambition of mitigation, however, global oil trade is projected to significantly decrease. One important aspect is that development pathways characterized by lower energy intensity (EI) are often likely to rely more heavily on oil than mitigation scenarios with conventional EI assumptions (see Figure S-6.5) because the mitigation options in the transport sectors are among those with the highest costs (Kriegler *et al* 2014b). Theoretically, the mitigation costs saved from lower EI could be used to lower the energy security risks around the reliance of the transport sector on oil.

For the purpose of this letter, the indicator refers to the percentage change in global oil imports, i.e. the sum of positive "Trade|Primary Energy|Oil|Volume" in each region *r* between 2020 and 2050 (*Trade_Oil*) relative to the baseline scenario.

$$\frac{\sum_r Trade\_Oil_r^{\mathrm{Mitigation}} - \sum_r Trade\_Oil_r^{\mathrm{Baseline}}}{\sum_r Trade\_Oil_r^{\mathrm{Baseline}}} \cdot 100\%$$

Cumulative oil extraction

For the robustness perspective related to oil security, we measure the cumulative extraction of oil resources as a relevant indicator for judging scarcity concerns (Jewell *et al* 2014). While the ‘peak-oil’ theory is still debated, even the perception of resource scarcity can lead to price volatility (McCollum *et al* 2013). Although global conventional oil reserves are limited, oil demand projections often exceed these already by 2050 in baseline scenarios (Rogner *et al* 2012). An alternative to conventional oil reserves would be to draw on so-called unconventional oil reserves. This alternative is, however, problematic, as there is considerable evidence that unconventional oil production involves bigger environmental and health risks as well as an increased carbon intensity of production, relative to conventional oil production (Bruckner *et al* 2014, Rogner *et al* 2012). For instance, Canada’s oil sands production appears to generate three times as many GHG emissions as its conventional oil production. Moreover, it is plausible that part of the water used in oil sands production pollutes the ground water. There is also evidence of it altering ecosystems (Engemann and Owyang 2010, Woynillowicz *et al* 2005).

Analogously, the production of oil shale has also been found to emit more GHGs than conventional oil production, decrease water quality, and permanently change ecosystems (Bartis *et al* 2005, Engemann and Owyang 2010). As a final example, Rogner *et al* (2012, p. 437) note that “severe soil and water contamination by chlorinated hydrocarbons and heavy metals” is likely to result from the processing of raw unconventional oil into sellable oil.

For the purpose of this letter, the indicator refers to the percentage change in the cumulative extraction of crude oil – "Resource|Cumulative Extraction|Oil" (*Oil*) – between 2020 and 2050 relative to the baseline scenario.

$$\frac{Oil^{\text{Mitigation}} - Oil^{\text{Baseline}}}{Oil^{\text{Baseline}}} \cdot 100\%$$

Fuel diversity of transport sector

For the resilience perspective, we measure the fuel diversity of the transport sector which currently is very low in most countries of the world due to high reliance on oil (Cherp *et al* 2012). For countries that are net importers of oil, the exposure to volatile and unpredictable oil prices affects the terms of trade and their economic stability (Sathaye *et al* 2011). Electrification of the transport sector and switching to biofuels would decrease the oil dependency by diversifying the energy supply, thus increasing resilience (Jewell *et al* 2014). Although mitigation scenarios often project less oil demand by 2050 relative to baseline developments, cost-effective technological options in the transport sector to substitute oil are still limited (Sims *et al* 2014). Global roll-out of alternative propulsion technology, particularly in the individual mobility sector, is likely to require clear price signals in many countries (either through global cooperation on carbon pricing or transport sector innovation) to spread the enormous investment costs in R&D, early deployment and diffusion (Bosetti *et al* 2011).

For the purpose of this letter, the indicator refers to the percentage change in the Shannon Wiener Diversity Index (SWDI) – multiplied by -1 to measure transport sector oil reliance, a SD risk, rather than fuel diversity of the transport sector, a policy objective – of the five most widely used final energy carriers in the transport sector – oil (‘Final Energy|Transportation|Liquids|Oil’), biofuels (‘Final Energy|Transportation|Liquids|Biomass’), gases (‘Final Energy|Transportation|Gases’), electricity (‘Final Energy|Transportation|Electricity’), and hydrogen (‘Final Energy|Transportation|Hydrogen’). The SWDI is the sum of the share of each final energy carrier (*f*) in total final transport energy (‘Final Energy|Transportation’) (*t*) multiplied by its natural logarithm.

$$\frac{\sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{ Mitigation}} - \sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{ Baseline}}}{\sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{ Baseline}}} \cdot 100\%$$

6.8.4 AMPERE model inter-comparison project

AMPERE is an EU-funded international effort that stands for ‘Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates’. This inter-comparison project of integrated models focused on the mitigation challenge of delayed and fragmented climate policy. AMPERE compares results from a wide range of internationally recognized energy-economy-climate models with different functional structures, parametric assumptions, and sectoral coverage (see Table S-6.1). The model diversity allowed identifying model uncertainty (i.e. where model results differed widely) and robust insights (i.e. where model results were similar).

AMPERE covered several key aspects not assessed in previous inter-comparison projects:

- Impact of short-term climate policies on the achievability of long-term mitigation goals;
- Role of individual technologies within the mitigation technology portfolio;
- Harmonization of key socioeconomic drivers (GDP, population and energy demand growth);
- Economic effects and climate benefits of early unilateral followed by delayed global action;
- Costs and benefits of alternative European Union climate policy choices;
- Diagnosing model behavior and assessing model validity to better understand differences.

The first two aspects are particularly important for this letter's analysis which is why the respective scenario specifications are described in more detail in Table S-6.3. The third point is also of importance for this analysis (see discussion) since harmonized key socioeconomic drivers allow a better mapping of the changes in the model variables to climate policy signals across models. The main finding of AMPERE is that any emissions resulting from low-ambitious short-term climate policies (until 2030) would need to be compensated over a relatively short timeframe (2030-2050) to stay within the limited carbon budget associated with restricting warming to 2°C (see Figure S-6.3).

Mitigation scenarios with low-ambitious short-term climate policies ("HST") would require quadrupling the low-carbon energy share and global CO_2 emission cuts of 6-8% per year in the two decades between 2030 and 2050. This means that almost half the global energy supply infrastructure would require replacement over a narrow two decade period. In optimal immediate climate policy scenarios ("OPT"), the energy system transition between 2030 and 2050 required to limit warming to 2°C would still be highly challenging, requiring a doubling of the low-carbon energy share and carbon intensity reductions of 3-4% per year (see Figure S-6.4).

The AMPERE models project a global mean warming of 3.5 – 5.9°C above pre-industrial levels by 2100 for the baseline scenarios, depending on the uncertainty in emissions and climate parameters (Table S-6.2). By contrast, all mitigation scenarios that are analyzed in this letter are scenarios designed to stay within the cumulative emission budget of 1500 $GtCO_2$ (2000–2100) – which largely corresponds to the mitigation scenarios with 450 ppm CO_2-equivalent concentrations at the end of the century (Clarke *et al* 2014, Riahi *et al* 2015, Schaeffer *et al* 2015). For median assumptions, this implies a 42-47% probability of not exceeding the 2°C target for all 450-FullTech scenarios which corresponds to maximum temperature changes of 2.5°C (see Table S-6.3).

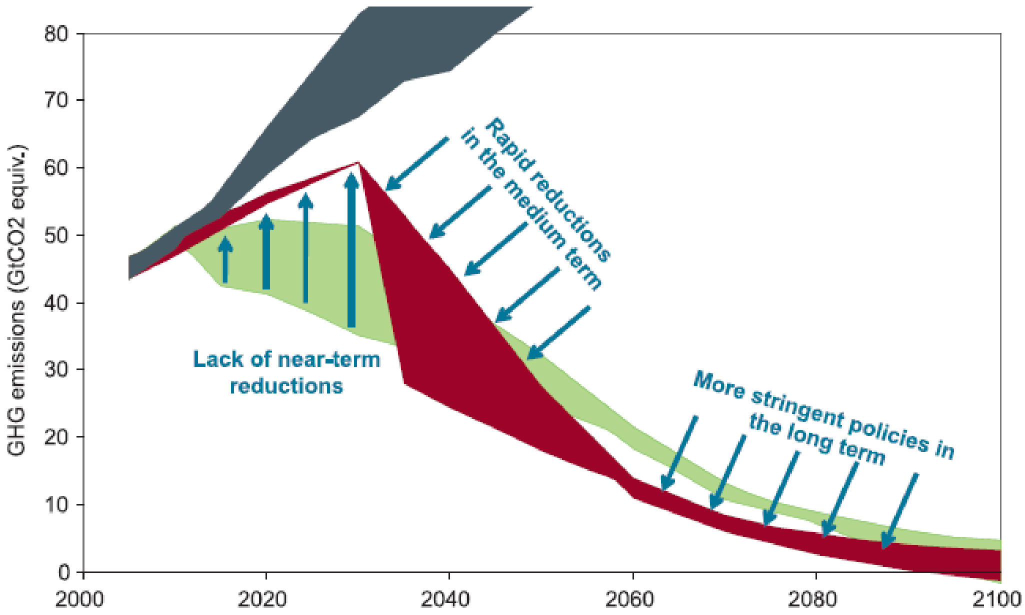

Figure S-6.3 GHG emission pathways of AMPERE models necessary to stay within the carbon budget consistent with the 2°C target. The optimal pathway with immediate mitigation is shown in green while the red emission pathway represents delayed 2°C pathways. The grey emission pathway denotes baseline development without climate policy. Source: Kriegler *et al* (2014a).

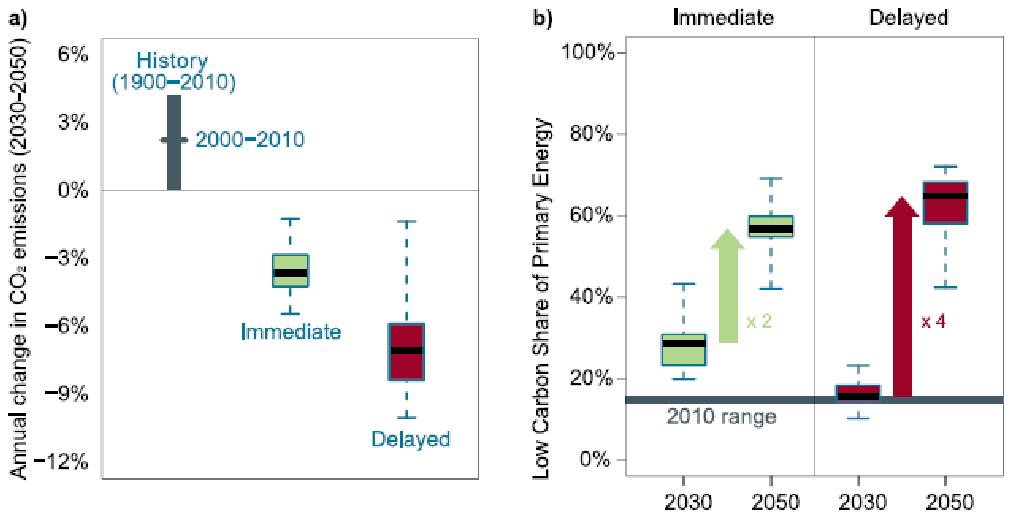

Figure S-6.4 Comparison of delayed and immediate mitigation pathways consistent with 2°C. Panel (a) illustrates the required carbon intensity reduction rates and panel (b) the required upscaling of low-carbon energy supply. Historical annual carbon intensity change rates from 1900 to 2010 (sustained over 20-year periods) are shown in grey in panel (a). Boxplots indicate median, interquartile and full ranges of model results. Source: Kriegler *et al* (2014a).

Table S-6.2 GHG emissions, atmospheric concentrations, and temperature consequences in the "FullTech" scenarios. Numbers correspond to the median and the full range across the scenarios. Note that for the climate simulations, emissions were harmonized to the same base year using inventories from Granier *et al* (2011) and Lamarque *et al* (2010) (adapted from Riahi *et al* 2015).

	CO_2 Emission (2030) $GtCO_2$	CO_2eq Emissions (2030) $GtCO_2$e	Cumulative CO_2 emissions (2000-2100) $GtCO_2$	CO_2eq concentrations (2100) ppm	Temperature change (max) °C	Probability of exceeding 2°C (max) %
Baseline	53 (50-67)	71 (68-83)	6,268 (5,670-8,755)	1,143 (1,023-1,338)	4.6 (3.5-5.9)	100 (100-100)
450 optimal	31 (24-45)	46 (35-60)	1,330 (1,242-1,350)	485 (453-522)	1.9 (1.5-2.4)	42 (26-84)
450 LST	39 (37-42)	53 (53-53)	1,335 (1,263-1,379)	488 (455-524)	2.0 (1.5-2.5)	45 (28-84)
450 HST	46 (44-49)	61 (60-61)	1,344 (1,274-1,382)	484 (452-520)	2.0 (1.6-2.5)	47 (28-84)

Table S-6.3 Mitigation technology choices and short-term climate policy stringencies assumed in the AMPERE scenarios (adapted from Riahi *et al* 2015).

Short-term targets (2030)	Description	Scenario name
Low short-term target	Global emissions follow a high ambition pledge pathway reaching 53 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"LST"
High short-term target	Global emissions follow a low ambition pledge pathway reaching 61 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"HST"
Optimal policy	Global emissions follow an optimal pathway assuming immediate introduction of climate policies to meet the long-term target (450 ppm CO_2eq). No explicit short-term target for 2030 is assumed.	"OPT"
Technology cases	**Description**	**Scenario name**
Full technology	The full portfolio of technologies is available and may scale up successfully to meet the respective climate targets	"FullTech"
Low Demand and Energy Intensity	A combination of stringent efficiency measures and behavioural changes radically limits energy demand, leading to a doubling of the rate energy intensity improvements compared to the past. The full portfolio of technologies is available on the supply side.	"LowEI"
No new nuclear	No new investments into nuclear power after 2020; existing plants are fully phased out over their lifetime.	"NucOff"
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate "negative emissions" when combined with bioenergy.	"NoCCS"
Limited Solar and Wind	Limited contribution of solar and wind to 20% of total power generation, reflecting potential implementation barriers of variable renewable energy at high penetration rates	"LimSW"
Limited Biomass	Limited potential for biomass (maximum of 100 EJ/yr), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fibre	"LimBio"

6.8.5 Supplementary figures

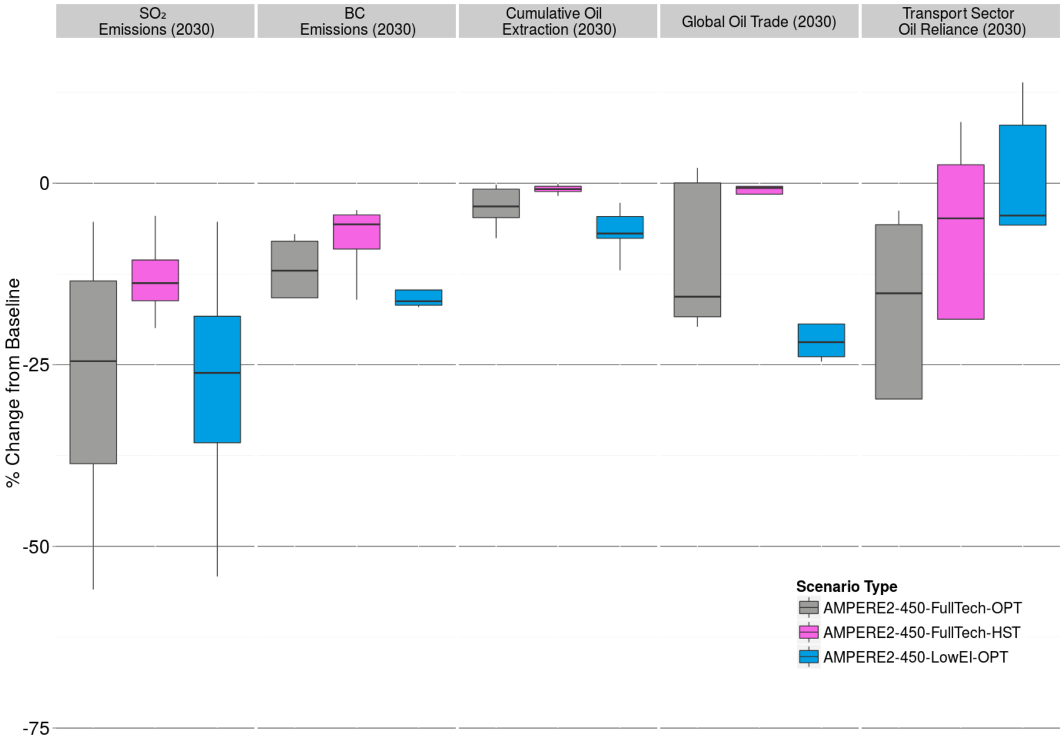

Figure S-6.5 Percentage changes in indicators for co-benefits for air quality, oil security and fuel diversity in the transport sector in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios in 2030, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). The thick coloured lines show median results, coloured ranges show interquartile ranges and whiskers show the minimum and maximum results.

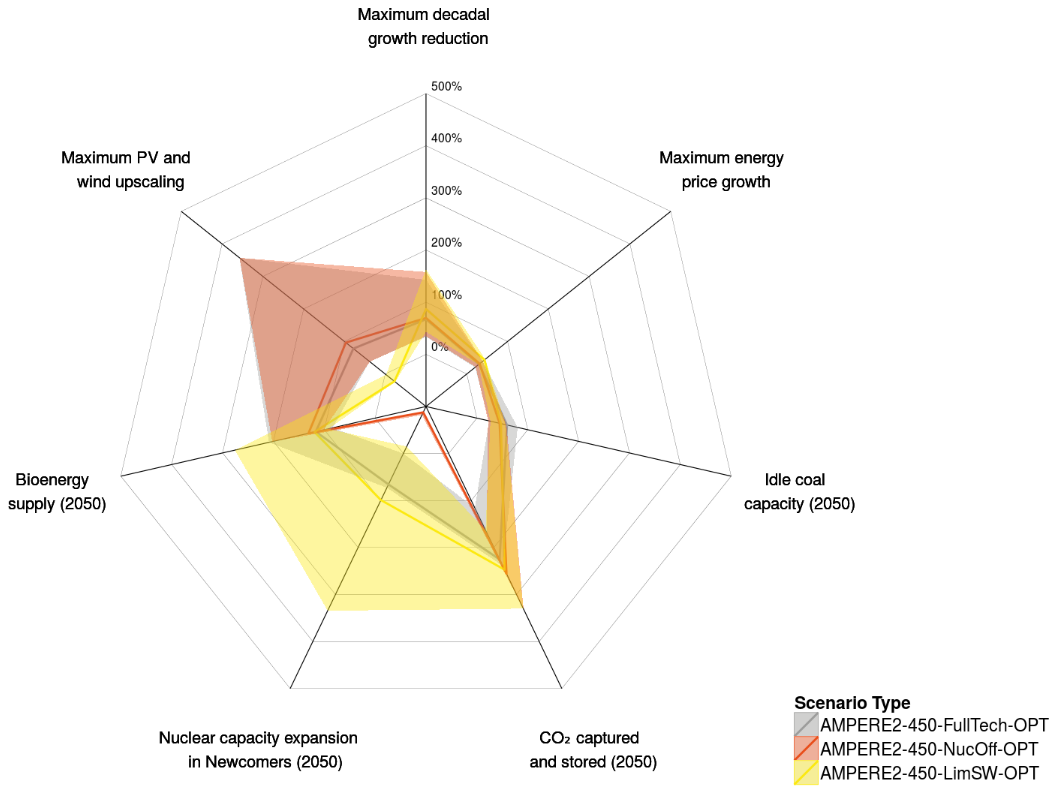

Figure S-6.6 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for five integrated models (GCAM, IMAGE, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with mitigation scenarios assuming no new nuclear capacity (red) or limited potential for solar and wind energy (yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

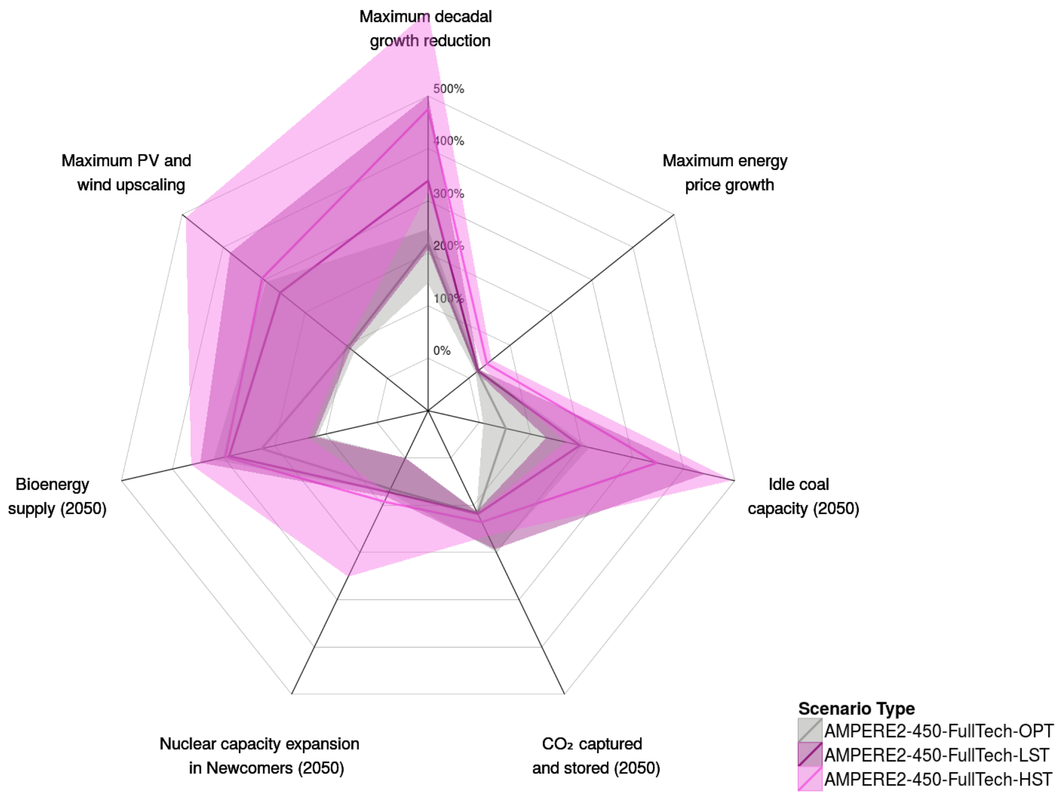

Figure S-6.7 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios with high short-term targets (pink) or low short-term targets (purple). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

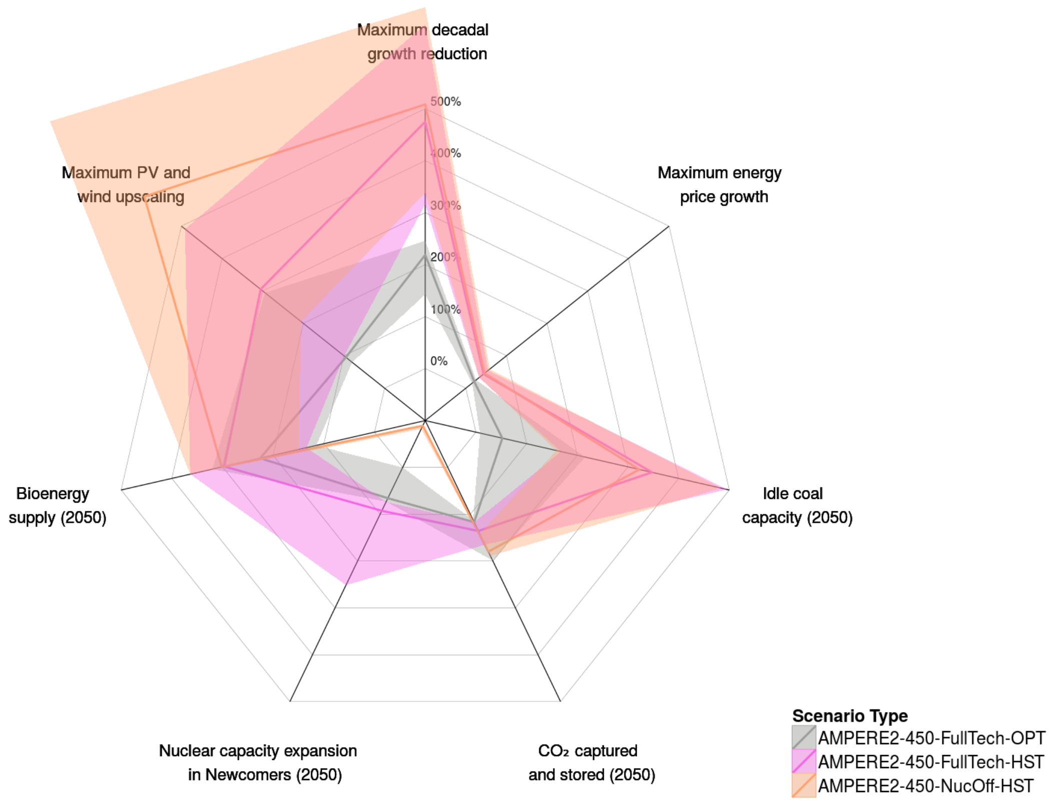

Figure S-6.8 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or no new nuclear capacity (red). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

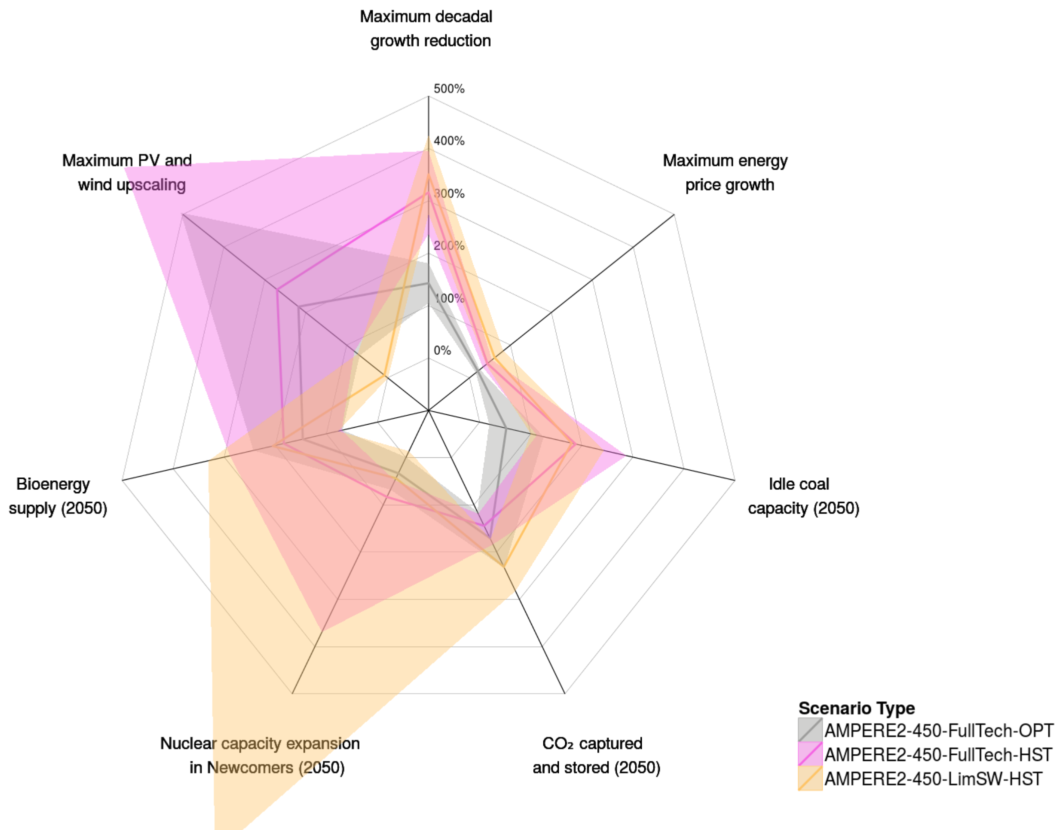

Figure S-6.9 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or limited potential for solar and wind energy (warm yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

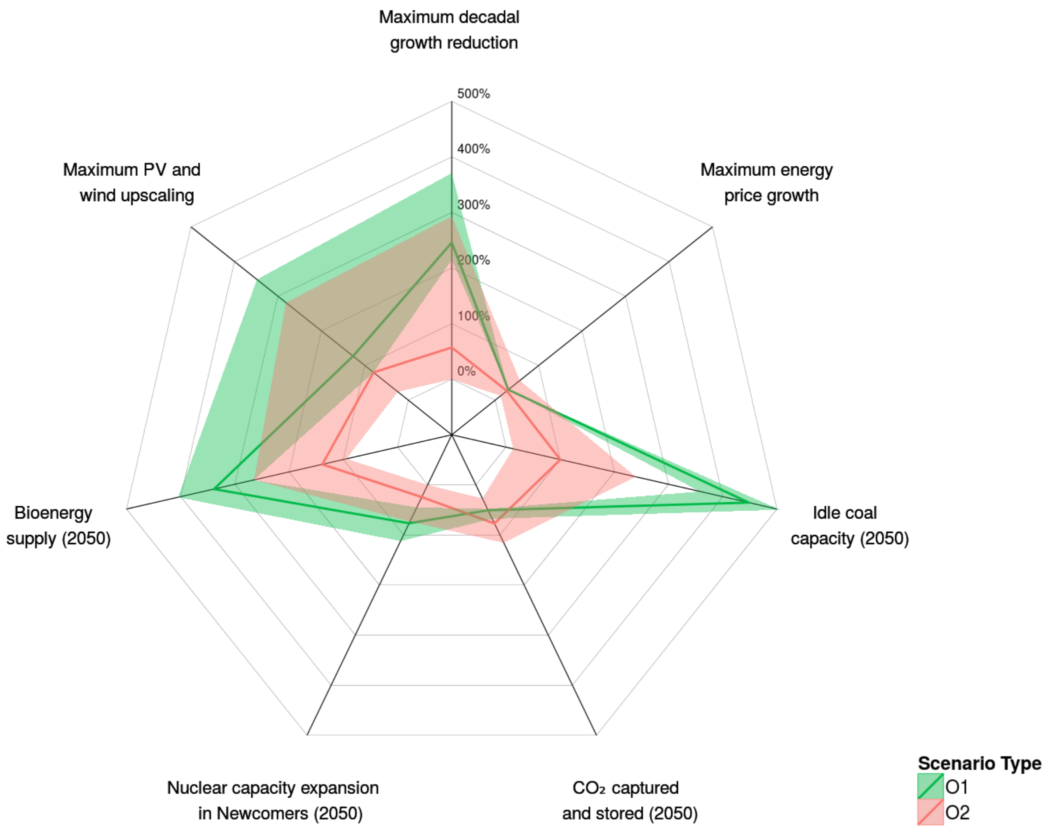

Figure S-6.10 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2050 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

Figure S-6.11 Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2080 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

Table S-6.4 Data underlying Figure 6.5. Percentage changes in median values of indicators for SD risk dimensions in different constrained 2°C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth).

Mitigation scenario	Indicator	Median value of indicator...	Median value of 'optimal' 2°C scenario...	Percentage change [%]	Year(s)	DNE21 V.12	GCAM 3.0	MESSAGE V.4	POLES AMPERE	REMIND 1.5	WITCH_ AMPERE
		...of the respective models									
AMPERE2-450-FullTech-OPT	Cumulative CO_2 Emissions [Gt]	812896,90	812896,90	**0,0**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative CO_2 Emissions [Gt]	813594,96	812896,90	**0,1**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative CO_2 Emissions [Gt]	805455,62	873256,50	**-1,6**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative CO_2 Emissions [Gt]	676945,25	873256,50	**-24,2**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative CO_2 Emissions [Gt]	721414,77	873256,50	**-27,9**	2020-50	x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative CO_2 Emissions [Gt]	821073,44	812896,90	**0,2**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative CO_2 Emissions [Gt]	843678,04	812896,90	**7,6**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative CO_2 Emissions [Gt]	842362,81	812896,90	**7,5**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative CO_2 Emissions [Gt]	901729,82	873256,50	**3,4**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative CO_2 Emissions [Gt]	781099,87	873256,50	**-6,7**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative CO_2 Emissions [Gt]	812376,62	1026093,61	**-17,2**	2020-50	x	x				
AMPERE2-450-LowEI-LST	Cumulative CO_2 Emissions [Gt]	864305,32	812896,90	**11,7**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative SO_2 Emissions [Gt]	1748,35	1748,35	**0,0**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative SO_2 Emissions [Gt]	1738,58	1748,35	**0,0**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative SO_2 Emissions [Gt]	1509,10	1560,63	**-3,3**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative SO_2 Emissions [Gt]	1324,99	1560,63	**-16,1**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative SO_2 Emissions [Gt]	1248,98	1748,35	**-22,2**	2020-50	x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative SO_2 Emissions [Gt]	1698,26	1748,35	**1,4**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative SO_2 Emissions [Gt]	1724,12	1748,35	**2,4**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative SO_2 Emissions [Gt]	1727,50	1748,35	**2,3**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative SO_2 Emissions [Gt]	1594,31	1560,63	**2,2**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative SO_2 Emissions [Gt]	1495,05	1560,63	**-2,7**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative SO_2 Emissions [Gt]	1782,04	2021,98	**-12,5**	2020-50	x	x				
AMPERE2-450-LowEI-LST	Cumulative SO_2 Emissions [Gt]	1753,20	1748,35	**7,3**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative BC Emissions [Gt]	186,11	186,11	**0,0**	2020-50	x	x	x		x	
AMPERE2-450-NucOff-OPT	Cumulative BC Emissions [Gt]	186,95	186,11	**0,0**	2020-50	x	x	x		x	
AMPERE2-450-LimSW-OPT	Cumulative BC Emissions [Gt]	172,44	176,57	**-2,3**	2020-50		x	x		x	
AMPERE2-450-LimBio-OPT	Cumulative BC Emissions [Gt]	167,65	176,57	**-8,9**	2020-50		x	x		x	
AMPERE2-450-NoCCS-OPT	Cumulative BC Emissions [Gt]	172,89	186,11	**-7,1**	2020-50	x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative BC Emissions [Gt]	166,20	168,89	**-1,6**	2020-50	x	x	x		x	
AMPERE2-450-FullTech-LST	Cumulative BC Emissions [Gt]	178,17	186,11	**-1,6**	2020-50	x	x	x		x	
AMPERE2-450-NucOff-LST	Cumulative BC Emissions [Gt]	178,99	186,11	**-1,1**	2020-50	x	x	x		x	
AMPERE2-450-LimSW-LST	Cumulative BC Emissions [Gt]	161,61	176,57	**-1,7**	2020-50		x	x		x	
AMPERE2-450-LimBio-LST	Cumulative BC Emissions [Gt]	159,42	176,57	**-9,7**	2020-50		x	x		x	
AMPERE2-450-NoCCS-LST	Cumulative BC Emissions [Gt]	203,10	212,57	**-4,7**	2020-50	x	x				
AMPERE2-450-LowEI-LST	Cumulative BC Emissions [Gt]	166,19	186,11	**-5,4**	2020-50	x	x	x		x	
AMPERE2-450-FullTech-OPT	Cumlative global oil trade [EJ]	3338,07	3338,07	**0,0**	2020-50		x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumlative global oil trade [EJ]	3369,41	3338,07	**-0,2**	2020-50		x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumlative global oil trade [EJ]	3294,56	3307,93	**-0,4**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumlative global oil trade [EJ]	3094,82	3307,93	**-8,1**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumlative global oil trade [EJ]	2881,66	3338,07	**-13,7**	2020-50		x	x		x	
AMPERE2-450-LowEI-OPT	Cumlative global oil trade [EJ]	3014,26	3338,07	**-8,0**	2020-50		x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumlative global oil trade [EJ]	3378,56	3338,07	**-0,5**	2020-50		x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumlative global oil trade [EJ]	3375,27	3338,07	**1,1**	2020-50		x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumlative global oil trade [EJ]	3307,45	3307,93	**-0,6**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-LST	Cumlative global oil trade [EJ]	3082,99	3307,93	**-6,8**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumlative global oil trade [EJ]	2875,70	3338,07	**-13,9**	2020-50		x				
AMPERE2-450-LowEI-LST	Cumlative global oil trade [EJ]	3087,27	3338,07	**-5,8**	2020-50		x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative oil extraction [EJ]	6149,59	6149,59	**0,0**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative oil extraction [EJ]	6144,59	6149,59	**-0,4**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative oil extraction [EJ]	6039,16	6149,59	**-1,7**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative oil extraction [EJ]	5142,31	6149,59	**-10,5**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative oil extraction [EJ]	5362,68	6451,85	**-17,1**	2020-50	x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative oil extraction [EJ]	5729,45	6149,59	**-7,0**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative oil extraction [EJ]	6016,11	6149,59	**0,6**	2020-50	x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative oil extraction [EJ]	6020,79	6149,59	**0,9**	2020-50	x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative oil extraction [EJ]	6082,86	6149,59	**-1,1**	2020-50		x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative oil extraction [EJ]	5134,03	6149,59	**-9,9**	2020-50		x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative oil extraction [EJ]	5560,36	6451,85	**-13,9**	2020-50	x	x				
AMPERE2-450-LowEI-LST	Cumulative oil extraction [EJ]	5683,63	6149,59	**-6,7**	2020-50	x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Fuel diversity of transport [SWDI]	-0,82	-0,82	**0,0**	2050	x	x	x	x	x	
AMPERE2-450-NucOff-OPT	Fuel diversity of transport [SWDI]	-0,78	-0,82	**-0,1**	2050	x	x	x	x	x	
AMPERE2-450-LimSW-OPT	Fuel diversity of transport [SWDI]	-0,91	-0,90	**-1,3**	2050		x	x	x	x	
AMPERE2-450-LimBio-OPT	Fuel diversity of transport [SWDI]	-1,03	-0,90	**-11,1**	2050		x	x	x	x	
AMPERE2-450-NoCCS-OPT	Fuel diversity of transport [SWDI]	-1,16	-0,88	**-31,2**	2050	x	x	x		x	
AMPERE2-450-LowEI-OPT	Fuel diversity of transport [SWDI]	-0,63	-0,82	**22,9**	2050	x	x	x	x	x	
AMPERE2-450-FullTech-LST	Fuel diversity of transport [SWDI]	-0,98	-0,82	**-2,8**	2050	x	x	x	x	x	
AMPERE2-450-NucOff-LST	Fuel diversity of transport [SWDI]	-0,99	-0,82	**-1,8**	2050	x	x	x	x	x	
AMPERE2-450-LimSW-LST	Fuel diversity of transport [SWDI]	-0,94	-0,90	**-4,8**	2050		x	x	x	x	
AMPERE2-450-LimBio-LST	Fuel diversity of transport [SWDI]	-1,09	-0,90	**-14,5**	2050		x	x	x	x	
AMPERE2-450-NoCCS-LST	Fuel diversity of transport [SWDI]	-1,38	-0,88	**-60,6**	2050	x	x				
AMPERE2-450-LowEI-LST	Fuel diversity of transport [SWDI]	-0,93	-0,82	**16,3**	2050	x	x	x	x	x	

AMPERE2-450-FullTech-OPT	Maximum transitional growth reduction	41,09	41,09	**0,0**	2020-50				x		x	x
AMPERE2-450-NucOff-OPT	Maximum transitional growth reduction	45,11	45,15	**33,8**	2020-50				x		x	x
AMPERE2-450-LimSW-OPT	Maximum transitional growth reduction	35,01	35,33	**32,3**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maximum transitional growth reduction	42,59	43,66	**107,5**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maximum transitional growth reduction	42,23	43,75	**152,0**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maximum transitional growth reduction	41,28	41,02	**-25,7**	2020-50				x		x	x
AMPERE2-450-FullTech-LST	Maximum transitional growth reduction	28,65	30,02	**119,4**	2020-50				x		x	x
AMPERE2-450-NucOff-LST	Maximum transitional growth reduction	28,62	30,07	**144,4**	2020-50				x		x	x
AMPERE2-450-LimSW-LST	Maximum transitional growth reduction	28,35	29,47	**112,5**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maximum transitional growth reduction	29,83	32,88	**304,3**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maximum transitional growth reduction	n/a	n/a	**n/a**	2020-50				x		x	
AMPERE2-450-LowEI-LST	Maximum transitional growth reduction	29,40	28,25	**-3,0**	2020-50				x		x	x
AMPERE2-450-FullTech-OPT	Maxium decadal energy price growth	1,33	1,33	**0,0**	2020-50				x		x	
AMPERE2-450-NucOff-OPT	Maxium decadal energy price growth	1,21	1,19	**1,8**	2020-50				x		x	
AMPERE2-450-LimSW-OPT	Maxium decadal energy price growth	1,40	1,30	**6,8**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maxium decadal energy price growth	1,46	1,30	**11,6**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maxium decadal energy price growth	1,62	1,30	**23,4**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maxium decadal energy price growth	1,21	1,21	**0,6**	2020-50				x		x	
AMPERE2-450-FullTech-LST	Maxium decadal energy price growth	1,38	1,23	**12,3**	2020-50				x		x	
AMPERE2-450-NucOff-LST	Maxium decadal energy price growth	1,40	1,23	**13,9**	2020-50				x		x	
AMPERE2-450-LimSW-LST	Maxium decadal energy price growth	1,52	1,23	**23,2**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maxium decadal energy price growth	2,24	1,28	**76,6**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maxium decadal energy price growth	n/a	n/a	**n/a**	2020-50							
AMPERE2-450-LowEI-LST	Maxium decadal energy price growth	1,40	1,28	**9,8**	2020-50				x		x	
AMPERE2-450-FullTech-OPT	Share of idle coal capacity	0,41	0,41	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Share of idle coal capacity	0,56	0,41	**-1,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Share of idle coal capacity	0,35	0,41	**1,1**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Share of idle coal capacity	0,77	0,41	**7,0**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Share of idle coal capacity	0,45	0,21	**7,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Share of idle coal capacity	0,43	0,41	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Share of idle coal capacity	0,85	0,41	**24,9**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Share of idle coal capacity	0,81	0,41	**17,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Share of idle coal capacity	0,81	0,41	**9,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Share of idle coal capacity	0,89	0,41	**19,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Share of idle coal capacity	0,59	0,17	**276,1**	2050		x	x				
AMPERE2-450-LowEI-LST	Share of idle coal capacity	0,83	0,41	**27,1**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	CO_2 captured & stored [Gt]	10844,76	10844,76	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	CO_2 captured & stored [Gt]	13638,38	10844,76	**22,4**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	CO_2 captured & stored [Gt]	17328,08	13521,52	**22,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	CO_2 captured & stored [Gt]	15836,94	13521,52	**-6,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	CO_2 captured & stored [Gt]	6807,59	10844,76	**-36,8**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	CO_2 captured & stored [Gt]	10925,85	10844,76	**-0,2**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	CO_2 captured & stored [Gt]	13307,78	10844,76	**14,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	CO_2 captured & stored [Gt]	16728,00	13521,52	**20,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	CO_2 captured & stored [Gt]	13920,23	13521,52	**-17,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x				
AMPERE2-450-LowEI-LST	CO_2 captured & stored [Gt]	6764,11	10844,76	**-34,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Nuclear capacity expansion in Newcomers [in GW]	166,94	166,94	**0,0**	2050			x	x	x	x	x
AMPERE2-450-NucOff-OPT	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-OPT	Nuclear capacity expansion in Newcomers [in GW]	141,73	210,52	**1,9**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Nuclear capacity expansion in Newcomers [in GW]	206,69	210,52	**45,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Nuclear capacity expansion in Newcomers [in GW]	600,81	254,10	**153,3**	2050			x	x		x	
AMPERE2-450-LowEI-OPT	Nuclear capacity expansion in Newcomers [in GW]	86,64	166,94	**-32,4**	2050			x	x	x	x	x
AMPERE2-450-FullTech-LST	Nuclear capacity expansion in Newcomers [in GW]	172,77	166,94	**3,5**	2050			x	x	x	x	x
AMPERE2-450-NucOff-LST	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-LST	Nuclear capacity expansion in Newcomers [in GW]	180,83	210,52	**18,3**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Nuclear capacity expansion in Newcomers [in GW]	255,71	210,52	**56,8**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Nuclear capacity expansion in Newcomers [in GW]	715,12	254,10	**181,4**	2050			x				
AMPERE2-450-LowEI-LST	Nuclear capacity expansion in Newcomers [in GW]	82,56	166,94	**-32,0**	2050			x	x	x	x	x
AMPERE2-450-FullTech-OPT	Bioenergy supply [EJ]	146,83	146,83	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Bioenergy supply [EJ]	150,44	146,83	**3,3**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Bioenergy supply [EJ]	168,30	162,96	**3,6**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Bioenergy supply [EJ]	108,54	162,96	**-35,3**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Bioenergy supply [EJ]	170,05	146,83	**11,6**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Bioenergy supply [EJ]	96,88	146,83	**-30,6**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Bioenergy supply [EJ]	148,49	146,83	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Bioenergy supply [EJ]	157,42	146,83	**6,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Bioenergy supply [EJ]	168,62	162,96	**3,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Bioenergy supply [EJ]	110,83	162,96	**-33,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Bioenergy supply [EJ]	216,14	132,83	**56,5**	2050		x	x				
AMPERE2-450-LowEI-LST	Bioenergy supply [EJ]	113,84	146,83	**-30,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Maximum PV and wind upscaling	2637,39	2637,39	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Maximum PV and wind upscaling	2631,82	2637,39	**23,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Maximum PV and wind upscaling	933,03	2637,39	**-66,3**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Maximum PV and wind upscaling	2737,18	2637,39	**8,8**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Maximum PV and wind upscaling	6079,59	3185,02	**57,3**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Maximum PV and wind upscaling	1033,60	2637,39	**-55,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Maximum PV and wind upscaling	2828,07	2637,39	**11,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Maximum PV and wind upscaling	2971,95	2637,39	**35,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Maximum PV and wind upscaling	1134,66	2637,39	**-57,0**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Maximum PV and wind upscaling	3574,35	2637,39	**49,3**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Maximum PV and wind upscaling	11495,02	2281,02	**268,8**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Maximum PV and wind upscaling	1591,21	2637,39	**-38,6**	2020-50		x	x	x	x	x	x

6.8.6 References

Aboumahboub T, Luderer G, Kriegler E, Leimbach M, Bauer N, Pehl M and Baumstark L 2014 On the regional distribution of climate mitigation costs: The impact of delayed cooperative action *Clim. Change Econ.* **05** 1440002

Ackerman F and Heinzerling L 2002 Pricing the priceless: Cost-benefit analysis of environmental protection *University of Pennsylvania Law Review* **150** 1553–84

Adibee N, Osanloo M and Rahmanpour M 2013 Adverse effects of coal mine waste dumps on the environment and their management *Environ Earth Sci* **70** 1581–92

Ahmed SA, Diffenbaugh NS and Hertel T W 2009 Climate volatility deepens poverty vulnerability in developing countries *Environ. Res. Lett.* **4** 034004

Akimoto K, Sano F, Homma T, Wada K, Nagashima M and Oda J 2012 Comparison of marginal abatement cost curves for 2020 and 2030: Longer perspectives for effective global GHG emission reductions *Sustain Sci* **7** 157–68

Allwood JM, Bosetti V, Dubash NK, Gómez-Echeverri L and von Stechow C 2014 Glossary *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1249–79

Amigun B, Musango JK and Stafford W 2011 Biofuels and sustainability in Africa *Renewable and Sustainable Energy Reviews* **15** 1360–72

Anenberg SC, Schwartz J, Shindell D, Amann M, Faluvegi G, Klimont Z, Janssens-Maenhout G, Pozzoli L, van Dingenen R, Vignati E, Emberson L, Muller NZ, West JJ, Williams M, Demkine V, Hicks WK, Kuylenstierna J, Raes F and Ramanathan V 2012 Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls *Environ Health Perspect* **120** 831–9

Apps JA, Zheng L, Zhang Y, Xu T and Birkholzer JT 2010 Evaluation of Potential Changes in Groundwater Quality in Response to CO_2 Leakage from Deep Geologic Storage *Transp Porous Med* **82** 215–46

Arndt C, Pauw K and Thurlow J 2012 Biofuels and economic development: A computable general equilibrium analysis for Tanzania *Energy Economics* **34** 1922–30

Atchley AL, Maxwell RM and Navarre-Sitchler AK 2013 Human health risk assessment of CO_2 leakage into overlying aquifers using a stochastic, geochemical reactive transport approach *Environ. Sci. Technol.* **47** 5954–62

Babiker MH and Eckaus RS 2007 Unemployment effects of climate policy *Environmental Science & Policy* **10** 600–9

Bartis JT, LaTourrette T, Dixon L, Peterson DJ and Cecchine G 2005 *Oil Shale Development in the United States* (Santa Monica, CA, Arilngton, VA, Pittsburgh, PA: RAND Corporation) Online: http://www.rand.org/pubs/monographs/MG414.html

Bauer N, Baumstark L and Leimbach M 2011 The REMIND-R model: The role of renewables in the low-carbon transformation—first-best vs. second-best worlds *Climatic Change* **114** 145–68

Bazilian M, Nussbaumer P, Eibs-Singer C, Brew-Hammond A, Modi V, Sovacool B, Ramana V and Aqrawi P-K 2012 Improving access to modern energy services: Insights from case studies *The Electricity Journal* **25** 93–114

Bell ML, Davis DL, Cifuentes LA, Krupnick AJ, Morgenstern RD and Thurston GD 2008 Ancillary human health benefits of improved air quality resulting from climate change mitigation *Environmental Health* **7** 41

Benson S, Cook P, Anderson J, Bachu S, Nimir HB, Basu B, Bradshaw J, Deguchi G, Gale J, von Goerne G et al. 2005 Underground geological storage *IPCC Special Report on Carbon Dioxide Capture and Storage* (Cambridge University Press, Cambridge, UK, and New York, NY, USA) pp 195–276

Bertram C, Johnson N, Luderer G, Riahi K, Isaac M and Eom J 2015a Carbon lock-in through capital stock inertia associated with weak near-term climate policies *Technological Forecasting and Social Change* **90, Part A** 62–72

Bertram C, Luderer G, Pietzcker RC, Schmid E, Kriegler E and Edenhofer O 2015b Complementing carbon prices with technology policies to keep climate targets within reach *Nature Climate Change* **5** 235–9

Blanchard O and Wolfers J 2000 The role of shocks and institutions in the rise of European unemployment: The aggregate evidence *The Economic Journal* **110** 1–33

Böhringer C, Keller A and van der Werf E 2013 Are green hopes too rosy? Employment and welfare impacts of renewable energy promotion *Energy Economics* **36** 277–85

Bonsch M, Humpenöder F, Popp A, Bodirsky B, Dietrich J P, Rolinski S, Biewald A, Lotze-Campen H, Weindl I, Gerten D and Stevanovic M 2016 Trade-offs between land and water requirements for large-scale bioenergy production *Glob. Change Biol. Bioenergy* **8** 11–24

Borzoni M 2011 Multi-scale integrated assessment of soybean biodiesel in Brazil *Ecological Economics* **70** 2028–38

Bosetti V, Carraro C, Duval R and Tavoni M 2011 What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&D *Energy Economics* **33** 1313–20

Bosetti V, Carraro C, Galeotti M, Massetti E and Tavoni M 2006 WITCH - A World Induced Technical Change Hybrid Model *The Energy Journal* **27** 13–38

Bosetti V, Carraro C and Tavoni M 2009a Climate change mitigation strategies in fast-growing countries: The benefits of early action *Energy Economics* **31, Supplement 2** S144–51

Bosetti V, DeCian E, Sgobbi A and Tavoni M 2009b *The 2008 WITCH model: New model features and baseline* (Venice, Italy: FEEM Working Paper 85)

Boucher O, Halloran PR, Burke EJ, Doutriaux-Boucher M, Jones CD, Lowe J, Ringer MA, Robertson E and Wu P 2012 Reversibility in an Earth System model in response to CO_2 concentration changes *Environ. Res. Lett.* **7** 024013

Bouwman AF, Kram T and Klein Goldewijk K 2006 *Integrated modelling of global environmental change - An overview of IMAGE 2.4* (Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency (MNP))

Bovenberg AL and van der Ploeg F 1994 Environmental policy, public finance and the labour market in a second-best world *Journal of Public Economics* **55** 349–90

von Braun J, Ahmed A, Asenso-Okyere K, Fan S, Gulati A, Hoddinott J, Pandya-Lorch R, Rosegrant MW, Ruel M, Torero M and van Rheenen T 2008 *High Food Prices: The What, Who, and How of Proposed Policy Actions* (Washington D.C.: International Food Policy Research Institute)

Bruckner T, Bashmakov I A, Mulugetta Y, Chum H, de la Vega Navarro A, Edmonds J, Faaij A, Fungtammasan B, Garg A, Hertwich E, Honnery D, Infield D, Kainuma M, Khennas S, Kim S, Nimir HB, Riahi K, Strachan N, Wiser R and Zhang X 2014 Energy Systems *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 511–97

Brunner S, Flachsland C and Marschinski R 2012 Credible commitment in carbon policy *Climate Policy* **12** 255–71

Bustamante M, Robledo-Abad C, Harper R, Mbow C, Ravindranat NH, Sperling F, Haberl H, de Siqueira Pinto A and Smith P 2014 Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector *Glob Change Biol* **20** 3270–90

Cai W, Wang C, Chen J and Wang S 2011 Green economy and green jobs: Myth or reality? The case of China’s power generation sector *Energy* **36** 5994–6003

Calvin K, Edmonds J, Bond-Lamberty B, Clarke L, Kim SH, Kyle P, Smith SJ, Thomson A and Wise M 2009 2.6: Limiting climate change to 450 ppm CO_2 equivalent in the 21st century *Energy Economics* **31, Supplement 2** S107–20

Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J 2014 Trade-offs of different land and bioenergy policies on the path to achieving climate targets *Climatic Change* **123** 691–704

Calvin K, Wise M, Luckow P, Kyle P, Clarke L and Edmonds J 2016 Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions *Climatic Change* **136** 57–68

Cameron C, Pachauri S, Rao ND, McCollum DL, Rogelj J and Riahi K 2016 Policy trade-offs between climate mitigation and clean cook-stove access in South Asia *Nature Energy* **1** 15010

Cao L and Caldeira K 2008 Atmospheric CO_2 stabilization and ocean acidification *Geophys. Res. Lett.* **35** L19609

Cao L, Caldeira K and Jain AK 2007 Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation *Geophys. Res. Lett.* **34** L05607

Casillas CE and Kammen DM 2010 The energy-poverty-climate nexus *Science* **330** 1181–1182

Cherp A, Adenikinju A, Goldthau A, Hernandez F, Hughes L, Jansen JC, Jewell J, Olshanskaya M, Soares de Oliveira R, Sovacool BK and Vakulenko S 2012 Chapter 5 - Energy and Security *Global Energy Assessment: Toward a More Sustainable Future* (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria: Cambridge University Press) pp 325–83

Cherp A and Jewell J 2014 The concept of energy security: Beyond the four As *Energy Policy* **75** 415–21

Cherp A and Jewell J 2011 The three perspectives on energy security: Intellectual history, disciplinary roots and the potential for integration *Current Opinion in Environmental Sustainability* **3** 202–12

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Goss Eng G, Lucht W, Mapako M, Masera Cerutti O, McIntyre T, Minowa T and Pingoud K 2011 Bioenergy *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 209–331

Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, Krey V, Kriegler E, Löschel A, McCollum D, Paltsev S, Rose S, Shukla PR, Tavoni M, van der Zwaan B and van Vuuren DP 2014 Assessing Transformation Pathways *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 413–506

Clarke L, Lurz M, Wise M, Edmonds J, Kim S, Smith SJ and Pitcher H 2007 *Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a.* (PNNL Technical Report. PNNL-16735)

Clinch JP and Healy JD 2001 Cost-benefit analysis of domestic energy efficiency *Energy Policy* **29** 113–24

Corsten M, Ramírez A, Shen L, Koornneef J and Faaij A 2013 Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature *International Journal of Greenhouse Gas Control* **13** 59–71

Creutzig F, Corbera E, Bolwig S and Hunsberger C 2013 Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment *Environ. Res. Lett.* **8** 035047

Creutzig F, Popp A, Plevin RJ, Luderer G, Minx J and Edenhofer O 2012a Reconciling top-down and bottom-up modeling on future bioenergy deployment *Nature Climate Change* **2** 320–7

Creutzig F, von Stechow C, Klein D, Hunsberger C, Bauer N, Popp A and Edenhofer O 2012b Can bioenergy assessments deliver? *Economics of Energy & Environmental Policy* **1** 65–82

Criqui P and Mima S 2012 European climate–energy security nexus. A model based scenario analysis *Energy Policy* **41** 827–42

Crivelli E, Furceri D and Toujas-Bernate J 2012 *Can Policies Affect Employment Intensity of Growth? A Cross-Country Analysis* (Rochester, NY: Social Science Research Network) Online: http://papers.ssrn.com/abstract=2169762

Daioglou V, van Ruijven BJ and van Vuuren DP 2012 Model projections for household energy use in developing countries *Energy* **37** 601–15

DeCian E, Bosetti V and Tavoni M 2011 Technology innovation and diffusion in “less than ideal” climate policies: An assessment with the WITCH model *Climatic Change* **114** 121–43

De Fraiture C, Giordano M and Liao Y 2008 Biofuels and implications for agricultural water use: Blue impacts of green energy *Water Policy* **10** 67–81

van Dingenen R, Dentener FJ, Raes F, Krol MC, Emberson L and Cofala J 2009 The global impact of ozone on agricultural crop yields under current and future air quality legislation *Atmospheric Environment* **43** 604–18

Dowling P and Russ P 2012 The benefit from reduced energy import bills and the importance of energy prices in GHG reduction scenarios *Energy Economics* **34, Supplement 3** S429–35

Duvenage I, Taplin R and Stringer LC 2012 Towards implementation and achievement of sustainable biofuel development in Africa *Environment, Development and Sustainability* **14** 993–1012

Edenhofer O, Kadner S, von Stechow C, Schwerhoff G and Luderer G 2014 Linking Climate Change Mitigation Research to Sustainable Development *Handbook of Sustainable Development* ed G Atkinson, S Dietz, E Neumayer and M Agarwala (Cheltenham, UK: Edward Elgar. 2nd Ed.) pp 476–99

Ekholm T, Soimakallio S, Moltmann S, Höhne N, Syri S and Savolainen I 2010 Effort sharing in ambitious, global climate change mitigation scenarios *Energy Policy* **38** 1797–810

den Elzen M and Höhne N 2008 Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets *Climatic Change* **91** 249–74

den Elzen MGJ, Lucas PL and van Vuuren DP 2008 Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations *Climatic Change* **90** 243–68

Engemann KM and Owyang MT 2010 Unconventional oil production: Stuck in a rock and a hard place *The Federal Reserve Bank of St. Louis' The Regional Economist* **18** 14–5

Ewing M and Msangi S 2009 Biofuels production in developing countries: Assessing tradeoffs in welfare and food security *Environmental Science & Policy* **12** 520–8

Fankhauser S, Sehlleier F and Stern N 2008 Climate change, innovation and jobs *Climate Policy* **8** 421–9

Farrell AE, Zerriffi H and Dowlatabadi H 2004 Energy infrastructure and security *Annual Review of Environment and Resources* **29** 421–69

Finco MVA and Doppler W 2010 Bioenergy and sustainable development: The dilemma of food security and climate change in the Brazilian savannah *Energy for Sustainable Development* **14** 194–9

Fischedick M, Schaeffer R, Adedoyin A, Akai M, Bruckner T, Clarke L, Krey V, Savolainen I, Teske S and Ürge-Vorsatz D 2011 Mitigation Potential and Costs *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 791–864

Fisher BS, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, Hourcade J-C, Jiang K, Kainuma M, la Rovere E, Matysek A, Rana A, Riahi K, Richels R, Rose S, van Vuuren D and Warren R 2007 Issues Related to Mitigation in the Long-Term Context *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]* (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169–250)

Fleurbaey M, Kartha S, Bolwig S, Chee YL, Chen Y, Corbera E, Lecocq F, Lutz W, Muylaert MS, Norgaard RB, Okereke C and Sagar AD 2014 Sustainable Development and Equity *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 283–350

Fleurbaey M and Zuber S 2012 Climate Policies Deserve a Negative Discount Rate *Chi. J. Int'l L.* **13** 565
Frondel M, Ritter N, Schmidt CM and Vance C 2010 Economic impacts from the promotion of renewable energy technologies: The German experience *Energy Policy* **38** 4048–56
Frondel M, Schmidt CM, aus dem Moore N, Bruckner T, Kondziella H, Krawinkel H and Goldammer K 2012 Energiewende und steigende Strompreise: Wer trägt die Hauptlast der hohen Kosten? *ifo Schnelldienst* **65** 3–18
Frondel M, Sommer S and Vance C 2015 The burden of Germany's energy transition: An empirical analysis of distributional effects *Economic Analysis and Policy* **45** 89–99
Frumkin H 2002 Urban sprawl and public health. *Public Health Rep* **117** 201–17
Fullerton D and Metcalf GE 2001 Environmental controls, scarcity rents, and pre-existing distortions *Journal of Public Economics* **80** 249–67
Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C, Raupach MR, Sharifi A, Smith P and Yamagata Y 2014 Betting on negative emissions *Nature Clim. Change* **4** 850–3
GEA 2012 *Global Energy Assessment - Toward a Sustainable Future* (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria) Online: www.globalenergyassessment.org
German L and Schoneveld G 2012 A review of social sustainability considerations among EU-approved voluntary schemes for biofuels, with implications for rural livelihoods *Energy Policy* **51** 765–78
Giavi S, Moretti M, Bontadina F, Zambelli N and Schaub M 2014 Seasonal survival probabilities suggest low migration mortality in migrating bats *PLoS ONE* **9** e85628
Goldemberg J, Coelho ST and Guardabassi P 2008 The sustainability of ethanol production from sugarcane *Energy Policy* **36** 2086–97
Grainger CA and Kolstad CD 2010 Who Pays a Price on Carbon? *Environ Resource Econ* **46** 359–76
Granier C, Bessagnet B, Bond T, D'Angiola A, van der Gon HD, Frost GJ, Heil A, Kaiser JW, Kinne S, Klimont Z, Kloster S, Lamarque J-F, Liousse C, Masui T, Meleux F, Mieville A, Ohara T, Raut J-C, Riahi K, Schultz MG, Smith SJ, Thompson A, van Aardenne J, van der Werf GR and van Vuuren DP 2011 Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period *Climatic Change* **109** 163–90
Griffin B, Buisson P, Criqui P and Mima S 2013 White Knights: will wind and solar come to the rescue of a looming capacity gap from nuclear phase-out or slow CCS start-up? *Climatic Change* **123** 623–35
Guivarch C, Crassous R, Sassi O and Hallegatte S 2011 The costs of climate policies in a second-best world with labour market imperfections *Climate Policy* **11** 768–88
Guivarch C and Hallegatte S 2013 2C or not 2C? *Global Environmental Change* **23** 179–92
Haberl H, Mbow C, Deng X, Irwin EG, Kerr S, Kuemmerle T, Mertz O, Meyfroidt P and Turner I 2014 Finite land resources and competition *Rethinking Global Land Use in an Urban Era. MIT Press, Cambridge* Online: http://forskningsbasen.deff.dk/Share.external?sp=S9da8ee83-6e21-4a42-ba50-4cb882bd7d9e&sp=Sku
Hall J, Matos S, Severino L and Beltrão N 2009 Brazilian biofuels and social exclusion: Established and concentrated ethanol versus emerging and dispersed biodiesel *Journal of Cleaner Production* **17** S77–85

Heinävaara S, Toikkanen S, Pasanen K, Verkasalo PK, Kurttio P and Auvinen A 2010 Cancer incidence in the vicinity of Finnish nuclear power plants: An emphasis on childhood leukemia *Cancer Causes & Control* **21** 587–95

Hendriks C, Graus W and van Bergen F 2004 *Global carbon dioxide storage potential and costs* (Ecofys, Utrecht) Online: http://www.researchgate.net/profile/Wina_Crijns-Graus/publication/260095614_Global_carbon_dioxide_storage_potential_and_costs/links/02e7e52f8a006a9854000000.pdf

Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, Heath GA, Bergesen JD, Ramirez A, Vega MI and Shi L 2015 Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies *PNAS* **112** 6260–4

Hertwich EG, van der Voet E, Suh S, Tukker A, Huijbregts MAJ, Kazmierczyk P, Lenzen M, McNeely J and Morguchi Y 2010 *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials. A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management.* (UNEP/Earthprint) Online: http://www.unep.org/resourcepanel-old/Portals/24102/PDFs/PriorityProductsAndMaterials_Report.pdf

von Hippel F, Bunn M, Diakov A, Ding M, Goldston R, Katsuta T, Ramana MV, Suzuki T and Suyuan Y 2012 Chapter 14 - Nuclear Energy *Global Energy Assessment - Toward a Sustainable Future* (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria) pp 1069–130

Hirth L 2013 The market value of variable renewables: The effect of solar wind power variability on their relative price *Energy Economics* **38** 218–36

Hirth L and Ueckerdt F 2013 The Decreasing Market Value of Variable Renewables: Integration Options and Deadlocks *Transition to Renewable Energy Systems* ed D Stolten and V Scherer (Wiley-VCH Verlag GmbH & Co. KGaA) pp 75–92 Online: http://onlinelibrary.wiley.com/doi/10.1002/9783527673872.ch6/summary

Holttinen H 2012 Wind integration: experience, issues, and challenges *WENE* **1** 243–55

Holttinen H, Meibom P, Orths A, Lange B, O'Malley M, Tande JO, Estanqueiro A, Gomez E, Söder L, Strbac G, Smith JC and van Hulle F 2011 Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration *Wind Energ.* **14** 179–92

Hourcade J-C, Jaccard M, Bataille C and Ghersi F 2006 Hybrid modeling: New answers to old challenges introduction to the special issue of the energy journal *Energy Journal* **27** 1–11

Huang J, Yang J, Msangi S, Rozelle S and Weersink A 2012 Biofuels and the poor: Global impact pathways of biofuels on agricultural markets *Food Policy* **37** 439–51

Humpenöder F, Popp A, Dietrich JP, Klein D, Lotze-Campen H, Bonsch M, Bodirsky BL, Weindl I, Stevanovic M and Müller C 2014 Investigating afforestation and bioenergy CCS as climate change mitigation strategies *Environ. Res. Lett.* **9** 064029

IEA 2009 *Technology Roadmap: Carbon Capture and Storage* (Paris, France: Organisation for Economic Co-operation and Development/International Energy Agency (IEA)) Online: https://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2009.html

IEA 2012 *World Energy Outlook 2012* (Paris, France: Organisation for Economic Co-operation and Development/International Energy Agency (IEA)) Online: http://www.worldenergyoutlook.org/publications/weo-2012/

IPCC 2014 *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.*

IPTS 2010 *Prospective Outlook on Long-Term Energy Systems – POLES Manual, Version 6.1,* (Institute for Prospective Technological Studies (IPTS), European Commission Joint Research Centre) Online: http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/documents/POLESdescription.pdf

Jakob M and Steckel JC 2014 How climate change mitigation could harm development in poor countries *WIREs Clim Change* **5** 161–8

Jewell J 2011 Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs *Energy Policy* **39** 1041–55

Jewell J, Cherp A and Riahi K 2014 Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices *Energy Policy* **65** 743–60

Johansson B 2013 Security aspects of future renewable energy systems–A short overview *Energy* **61** 598–605

Johnson N, Krey V, McCollum DL, Rao S, Riahi K and Rogelj J 2015 Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants *Technological Forecasting and Social Change* **90, Part A** 89–102

Joos F, Fröhlicher TL, Steinacher M and Plattner G-K 2011 Impact of climate change mitigation on ocean acidification projections *Ocean Acidification* ed J-P Gattuso and L Hansson (Oxford, UK: Oxford University Press) pp 272–90

Kaatsch P, Spix C, Schulze-Rath R, Schmiedel S and Blettner M 2008 Leukaemia in young children living in the vicinity of German nuclear power plants *International Journal of Cancer* **122** 721–6

Kanagawa M and Nakata T 2007 Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries *Ecological Economics* **62** 319–29

Kim SH, Wada K, Kurosawa A and Roberts M 2014 Nuclear energy response in the EMF27 study *Climatic Change* **123** 443–60

Knopf B and Geden O 2014 A warning from the IPCC: the EU 2030's climate target cannot be based on science alone Online: http://www.energypost.eu/warning-ipcc-eu-2030s-climate-target-based-science-alone/

Koornneef J, van Keulen T, Faaij A and Turkenburg W 2008 Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2 *International Journal of Greenhouse Gas Control* **2** 448–67

Krey V, Masera O, Blanford G, Bruckner T, Cooke R, Fisher-Vanden K, Haberl H, Hertwich E, Kriegler E, Mueller D, Paltsev S, Price L, Schlömer S, Ürge-Vorsatz D, van Vuuren D and Zwickel T 2014 Annex II: Metrics & Methodology *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1281–328

Krey V, O'Neill BC, van Ruijven B, Chaturvedi V, Daioglou V, Eom J, Jiang L, Nagai Y, Pachauri S and Ren X 2012 Urban and rural energy use and carbon dioxide emissions in Asia *Energy Economics* **34, Supplement 3** S272–83

Kriegler E, Petermann N, Krey V, Schwanitz VJ, Luderer G, Ashina S, Bosetti V, Eom J, Kitous A, Méjean A, Paroussos L, Sano F, Turton H, Wilson C and van Vuuren DP 2015a Diagnostic indicators for integrated assessment models of climate policy *Technological Forecasting and Social Change* **90, Part A** 45–61

Kriegler E, Riahi K, Bauer N, Schwanitz VJ, Petermann N, Bosetti V, Marcucci A, Otto S, Paroussos L, Rao S, Arroyo Currás T, Ashina S, Bollen J, Eom J, Hamdi-Cherif M, Longden T, Kitous A, Méjean A, Sano F, Schaeffer M, Wada K, Capros P, van Vuuren DP and Edenhofer O 2015b Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy *Technological Forecasting and Social Change* **90, Part A** 24–44

Kriegler E, Riahi K, Petermann N, Bosetti V, Capros P, van Vuuren D, Criqui P, Egenhofer C, Fragkos P, Johnson N, Paroussos L, Behrens A, Edenhofer O and the AMPERE Consortium 2014a *Assessing pathways toward ambitious climate targets at the global and European levels. A synthesis of results from the AMPERE project* (Potsdam, Germany) Online: http://ampere-project.eu/web/images/Final_Conference/ampere_synthesis_5-2014-compact.pdf

Kriegler E, Tavoni M, Aboumahboub T, Luderer G, Calvin K, Demaere G, Krey V, Riahi K, Rösler H, Schaeffer M and van Vuuren DP 2013 What does the 2°C target imply for a global climate agreement in 2020? The limits study on Durban Platform scenarios *Clim. Change Econ.* **04** 1340008

Kriegler E, Weyant JP, Blanford GJ, Krey V, Clarke L, Edmonds J, Fawcett A, Luderer G, Riahi K, Richels R, Rose SK, Tavoni M and van Vuuren DP 2014b The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies *Climatic Change* **123** 353–67

Kruyt B, van Vuuren DP, de Vries HJM and Groenenberg H 2009 Indicators for energy security *Energy Policy* **37** 2166–81

Kunreuther H, Gupta S, Bosetti V, Cooke R, Dutt V, Ha-Duong M, Held H, Llanes-Regueiro J, Patt A, Shittu E and Weber E 2014 Integrated Risk and Uncertainty Assessment of Climate Change Response Policies *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 151–205

Lackey RT 2001 Values, Policy, and Ecosystem Health Options for resolving the many ecological policy issues we face depend on the concept of ecosystem health, but ecosystem health is based on controversial, value-based assumptions that masquerade as science *BioScience* **51** 437–43

Lamarque J-F, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, Lee D, Liousse C, Mieville A, Owen B, Schultz MG, Shindell D, Smith SJ, Stehfest E, van Aardenne J, Cooper OR, Kainuma M, Mahowald N, McConnell JR, Naik V, Riahi K and van Vuuren DP 2010 Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application *Atmos. Chem. Phys.* **10** 7017–39

Lambert RJ and Silva PP 2012 The challenges of determining the employment effects of renewable energy *Renewable and Sustainable Energy Reviews* **16** 4667–74

Lamb WF and Rao ND 2015 Human development in a climate-constrained world: What the past says about the future *Global Environmental Change* **33** 14–22

Lehnert LS, Kramer-Schadt S, Schönborn S, Lindecke O, Niermann I and Voigt CC 2014 Wind farm facilities in Germany kill noctule bats from near and far *PLoS ONE* **9** e103106

Lehr U, Lutz C and Edler D 2012 Green jobs? Economic impacts of renewable energy in Germany *Energy Policy* **47** 358–64

Leiby PN and Rubin J 2013 Energy security implications of a national low carbon fuel standard *Energy Policy* **56** 29–40

Leimbach M, Bauer N, Baumstark L and Edenhofer O 2009 Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R *Environ Model Assess* **15** 155–73

Leimbach M, Bauer N, Baumstark L, Lüken M and Edenhofer O 2010 Technological Change and International Trade - Insights from REMIND-R *The Energy Journal* **31** 109–36

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M, Anderson HR, Andrews KG, Aryee M, Atkinson C, Bacchus LJ, Bahalim AN, Balakrishnan K, Balmes J, Barker-Collo S, Baxter A, Bell ML, Blore JD, Blyth F, Bonner C, Borges G, Bourne R, Boussinesq M, Brauer M, Brooks P, Bruce NG, Brunekreef B, Bryan-Hancock C, Bucello C, Buchbinder R, Bull F, Burnett RT, Byers TE, Calabria B, Carapetis J, Carnahan E, Chafe Z, Charlson F, Chen H, Chen J S, Cheng AT-A, Child J C, Cohen A, Colson KE, Cowie BC, Darby S, Darling S, Davis A, Degenhardt L, Dentener F, Des Jarlais DC, Devries K, Dherani M, Ding EL, Dorsey ER, Driscoll T, Edmond K, Ali SE, Engell RE, Erwin PJ, Fahimi S, Falder G, Farzadfar F, Ferrari A, Finucane MM, Flaxman S, Fowkes FGR, Freedman G, Freeman MK, Gakidou E, Ghosh S, Giovannucci E, Gmel G, Graham K, Grainger R, Grant B, Gunnell D, Gutierrez HR, Hall W, Hoek HW, Hogan A, Hosgood HD, Hoy D, Hu H, Hubbell BJ, Hutchings SJ, Ibeanusi SE, Jacklyn GL, Jasrasaria R, Jonas JB, Kan H, Kanis JA, Kassebaum N, Kawakami N, Khang Y-H, Khatibzadeh S, et al 2012 A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010 *The Lancet* **380** 2224–60

Lotze-Campen H, von Lampe M, Kyle P, Fujimori S, Havlik P, van Meijl H, Hasegawa T, Popp A, Schmitz C, Tabeau A, Valin H, Willenbockel D and Wise M 2014 Impacts of increased bioenergy demand on global food markets: An AgMIP economic model intercomparison *Agricultural Economics* **45** 103–16

Lucas P L, Shukla PR, Chen W, van Ruijven BJ, Dhar S, den Elzen MGJ and van Vuuren DP 2013 Implications of the international reduction pledges on long-term energy system changes and costs in China and India *Energy Policy* **63** 1032–41

Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, Cabeza LF, Eyre N, Gadgil A, Harvey LDD, Jiang Y, Liphoto E, Mirasgedis S, Murakami S, Parikh J, Pyke C and Vilariño MV 2014 Buildings *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 671–738

Luderer G, Bertram C, Calvin K, DeCian E and Kriegler E 2016 Implications of weak near-term climate policies on long-term mitigation pathways *Climatic Change* **136** 127–140

Luderer G, De Cian E, Hourcade J-C, Leimbach M, Waisman H and Edenhofer O 2012 On the regional distribution of mitigation costs in a global cap-and-trade regime *Climatic Change* **114** 59–78

Luderer G, Leimbach M, Bauer N and Kriegler E 2011 *Description of the ReMIND-R Model, Technical Report* (Potsdam, Germany: Potsdam Institute for Climate Impact Research (PIK)) Online: www.pik-potsdam.de/research/sustainable-solutions/models/remind/REMIND_Description.pdf

Luderer G, Leimbach M, Bauer N, Kriegler E, Aboumahboub T, Curras TA, Baumstark L, Bertram C, Giannousakis A, Hilaire J, Klein D, Mouratiadou I, Pietzcker R, Piontek F, Roming N, Schultes A, Schwanitz VJ and Strefler J 2013a *Description of the REMIND Model (Version 1.5)* (Rochester, NY: Social Science Research Network) Online: http://papers.ssrn.com/abstract=2312844

Luderer G, Pietzcker RC, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013b Economic mitigation challenges: How further delay closes the door for achieving climate targets *Environ. Res. Lett.* **8** 034033

Marques AT, Batalha H, Rodrigues S, Costa H, Pereira MJR, Fonseca C, Mascarenhas M and Bernardino J 2014 Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies *Biological Conservation* **179** 40–52

Mathesius S, Hofmann M, Caldeira K and Schellnhuber HJ 2015 Long-term response of oceans to CO_2 removal from the atmosphere *Nature Clim. Change* **5** 1107–13

Mazzoldi A, Rinaldi AP, Borgia A and Rutqvist J 2012 Induced seismicity within geological carbon sequestration projects: Maximum earthquake magnitude and leakage potential from undetected faults *International Journal of Greenhouse Gas Control* **10** 434–42

McCollum DL, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013 Climate policies can help resolve energy security and air pollution challenges *Climatic Change* **119** 479–94

McMillan M, Rodrik D and Verduzco-Gallo Í 2014 Globalization, structural change, and productivity growth, with an update on Africa *World Development* **63** 11–32

Meldrum J, Nettles-Anderson S, Heath G and Macknick J 2013 Life cycle water use for electricity generation: A review and harmonization of literature estimates *Environ. Res. Lett.* **8** 015031

Messner S and Schrattenholzer L 2000 MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively *Energy* **25** 267–82

Moore R 2012 Definitions of fuel poverty: Implications for policy *Energy Policy* **49** 19–26

Nelson T, Simshauser P and Kelley S 2011 Australian residential solar feed-in tariffs: Industry stimulus or regressive form of taxation? *Economic Analysis and Policy* **41** 113–29

Oei P-Y, Gerbaulet C, Kemfert C, Kunz F, Reitz F and von Hirschhausen C 2015. *Effektive CO_2-Minderung im Stromsektor: Klima-, Preis-und Beschäftigungseffekte des Klimabeitrags und alternativer Instrumente* Online: http://www.diw.de/sixcms/detail.php?id=diw_01.c.509252.de

Orr JC, Fabry VJ, Aumont O, Bopp L, Doney SC, Feely RA, Gnanadesikan A, Gruber N, Ishida A, Joos F, Key RM, Lindsay K, Maier-Reimer E, Matear R, Monfray P, Mouchet A, Najjar RG, Plattner G-K, Rodgers KB, Sabine CL, Sarmiento JL, Schlitzer R, Slater RD, Totterdell IJ, Weirig M-F, Yamanaka Y and Yool A 2005 Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms *Nature* **437** 681–6

Pachauri S, van Ruijven BJ, Nagai Y, Riahi K, van Vuuren DP, Brew-Hammond A and Nakicenovic N 2013 Pathways to achieve universal household access to modern energy by 2030 *Environ. Res. Lett.* **8** 024015

Pachauri S and Spreng D 2004 Energy use and energy access in relation to poverty *Economic and Political Weekly* **39** 271–8

Palmer MA, Bernhardt ES, Schlesinger WH, Eshleman KN, Foufoula-Georgiou E, Hendryx MS, Lemly AD, Likens GE, Loucks OL, Power ME, White PS and Wilcock PR 2010 Mountaintop Mining Consequences *Science* **327** 148–9

Paltsev S and Capros P 2013 Cost concepts for climate change mitigation *Clim. Change Econ.* **04** 1340003

PBL 2012 *Roads from Rio+20. Pathways to achieve global sustainability goals by 2050* (The Hague, The Netherlands: Netherlands 3 Environmental Assessment Agency (PBL)) Online: http://www.pbl.nl/en/publications/2012/roads-from-rio20

Pindyck RS 2013 *Climate change policy: What do the models tell us? No. w19244* (National Bureau of Economic Research) Online: http://www.nber.org/papers/w19244

Popp A, Dietrich JP, Lotze-Campen H, Klein D, Bauer N, Krause M, Beringer T, Gerten D and Edenhofer O 2011 The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system *Environ. Res. Lett.* **6** 034017

Popp A, Rose SK, Calvin K, van Vuuren DP, Dietrich JP, Wise M, Stehfest E, Humpenöder F, Kyle P, van Vliet J, Bauer N, Lotze-Campen H, Klein D and Kriegler E 2014 Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options *Climatic Change* **123** 495–509

Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB and Travasso MI 2014 Food security and food production systems *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* ed CB Field, VR Barros, DJ Dokken, KJ Mach, MD Mastrandrea, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, B Girma, ES Kissel, AN Levy, S MacCracken, PR Mastrandrea and LL White (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) pp 485–533

Rao S, Pachauri S, Dentener F, Kinney P, Klimont Z, Riahi K and Schoepp W 2013 Better air for better health: Forging synergies in policies for energy access, climate change and air pollution *Global Environmental Change* **23** 1122–30

Rao S and Riahi K 2006 The Role of Non-CO_2 Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century *The Energy Journal* **27** 177–200

Ravallion M and Chen S 1997 What can new survey data tell us about recent changes in distribution and poverty? *World Bank Econ Rev* **11** 357–82

Riahi K, Grübler A and Nakicenovic N 2007 Scenarios of long-term socio-economic and environmental development under climate stabilization *Technological Forecasting and Social Change* **74** 887–935

Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, Eom J, Schaeffer M, Edmonds J, Isaac M, Krey V, Longden T, Luderer G, Méjean A, McCollum DL, Mima S, Turton H, van Vuuren DP, Wada K, Bosetti V, Capros P, Criqui P, Hamdi-Cherif M, Kainuma M and Edenhofer O 2015 Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals *Technological Forecasting and Social Change* **90, Part A** 8–23

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ and others 2009 A safe operating space for humanity *Nature* **461** 472–5

Rodrik D 2008 *One Economics, Many Recipes: Globalization, Institutions, and Economic Growth* (Princeton University Press)

Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V and Riahi K 2015 Energy system transformations for limiting end-of-century warming to below 1.5°C *Nature Clim. Change* **5** 519–27

Rogelj J, McCollum DL, O'Neill BC and Riahi K 2013a 2020 emissions levels required to limit warming to below 2°C *Nature Clim. Change* **3** 405–12

Rogelj J, McCollum DL and Riahi K 2013b The UN's "Sustainable Energy for All" initiative is compatible with a warming limit of 2°C *Nature Clim. Change* **3** 545–51

Rogelj J, Nabel J, Chen C, Hare W, Markmann K, Meinshausen M, Schaeffer M, Macey K and Höhne N 2010 Copenhagen Accord pledges are paltry *Nature* **464** 1126–8

Rogner H-H, Aguilera RF, Bertani R, Bhattacharya SC, Dusseault MB, Gagnon L, Haberl H, Hoogwijk M, Johnson A, Rogner ML, Wagner H and Yakushev V 2012 Chapter 7 - Energy Resources and Potentials *Global Energy Assessment - Toward a Sustainable Future* (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria) pp 423–512 Online: www.globalenergyassessment.org

Romero-Jordán D, del Río P and Peñasco C 2016 An analysis of the welfare and distributive implications of factors influencing household electricity consumption *Energy Policy* **88** 361–70

Rose SK, Ahammad H, Eickhout B, Fisher B, Kurosawa A, Rao S, Riahi K and van Vuuren DP 2012 Land-based mitigation in climate stabilization *Energy Economics* **34** 365–80

Rozenberg J, Vogt-Schilb A and Hallegatte S 2014 Transition to clean capital, irreversible investment and stranded assets *World Bank Policy Research Working Paper* **6859** Online: http://papers.ssrn.com/abstract=2433812

van Ruijven BJ, van Vuuren DP, van Vliet J, Mendoza Beltran A, Deetman S and den Elzen MGJ 2012 Implications of greenhouse gas emission mitigation scenarios for the main Asian regions *Energy Economics* **34, Supplement 3** S459–69

Ruiz Romero S, Colmenar Santos A and Castro Gil MA 2012 EU plans for renewable energy. An application to the Spanish case *Renewable Energy* **43** 322–30

Sagan SD 2011 The causes of nuclear weapons proliferation *Annual Review of Political Science* **14** 225–44

Sano F, Akimoto K, Homma T, Oda J and Wada K 2012 Analysis of Asian Long-term Climate Change Mitigation in Power Generation sector 3rd IAEE Asian Conference (Kyoto, Japan) Online: http://eneken.ieej.or.jp/3rd_IAEE_Asia/pdf/paper/044p.pdf

Sano F, Wada K, Akimoto K and Oda J 2015 Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro- and sectoral decomposition analyses *Technological Forecasting and Social Change* **90, Part A** 153–65

Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, Fujino J, Heath G, Kadner S, Mirza M, Rudnick H, Schlaepfer A and Shmakin A 2011 Renewable Energy in the Context of Sustainable Development *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 707–89

Schaeffer M, Gohar L, Kriegler E, Lowe J, Riahi K and van Vuuren D 2015 Mid- and long-term climate projections for fragmented and delayed-action scenarios *Technological Forecasting and Social Change* **90, Part A** 257–68

Schakel W, Meerman H, Talaei A, Ramírez A and Faaij A 2014 Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage *Applied Energy* **131** 441–67

Sermage-Faure C, Laurier D, Goujon-Bellec S, Chartier M, Guyot-Goubin A, Rudant J, Hémon D and Clavel J 2012 Childhood leukemia around French nuclear power plants—the Geocap study, 2002–2007 *International Journal of cancer* **131** E769–80

Shearer C, Ghio N, Myllyvirta L and Nace T 2015 *Boom and bust. Tracking the global coal plant pipeline* (CoalSwarm and Sierra Club) Online: http://action.sierraclub.org/site/DocServer/Coal_Tracker_report_final_3-9-15.pdf?docID=17381

Shindell D, Kuylenstierna JCI, Vignati E, van Dingenen R, Amann M, Klimont Z, Anenberg S C, Muller N, Janssens-Maenhout G, Raes F, Schwartz J, Faluvegi G, Pozzoli L, Kupiainen K, Höglund-Isaksson L, Emberson L, Streets D, Ramanathan V, Hicks K, Oanh NTK, Milly G, Williams M, Demkine V and Fowler D 2012 Simultaneously mitigating near-term climate change and improving human health and food security *Science* **335** 183–9

Siirila ER, Navarre-Sitchler AK, Maxwell RM and McCray JE 2012 A quantitative methodology to assess the risks to human health from CO_2 leakage into groundwater *Advances in Water Resources* **36** 146–64

Sims R, Mercado P, Krewitt W, Bhuyan G, Flynn D, Holttinen H, Jannuzzi G, Khennas S, Liu Y, Nilsson LJ, Ogden J, Ogimoto K, O'Malley M, Outhred H, Ulleberg Ø and van Hulle F 2011 Integration of Renewable Energy into Present and Future Energy Systems *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 609–706

Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, Dimitriu D, Figueroa Meza M J, Fulton L, Kobayashi S, Lah O, McKinnon A, Newman P, Ouyang M, Schauer JJ, Sperling D and Tiwari G 2014 Transport *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 599–670

Smith KR, Bruce N, Balakrishnan K, Adair-Rohani H, Balmes J, Chafe Z, Dherani M, Hosgood HD, Mehta S, Pope D and Rehfuess E 2014a Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution *Annual Review of Public Health* **35** 185–206

Smith KR, Frumkin H, Balakrishnan K, Butler CD, Chafe ZA, Fairlie I, Kinney P, Kjellstrom T, Mauzerall DL, McKone TE, McMichael AJ and Schneider M 2013 Energy and human health *Annual Review of Public Health* **34** 159–88

Smith KR and Haigler E 2008 Co-benefits of climate mitigation and health protection in energy systems: Scoping methods *Annual Review of Public Health* **29** 11–25

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig E A, Haberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath N H, Rice C W, Robledo Abad C, Romanovskaya A, Sperling F and Tubiello F 2014b Agriculture, Forestry and Other Land Use (AFOLU) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 811–922

Smith SJ and Mizrahi A 2013 Near-term climate mitigation by short-lived forcers *PNAS* **110** 14202–6

Söder L, Hofmann L, Orths A, Holttinen H, Wan Y-H and Tuohy A 2007 Experience from wind integration in some high penetration areas *IEEE Transactions on Energy Conversion* **22** 4–12

Sokona Y, Mulugetta Y and Gujba H 2012 Widening energy access in Africa: Towards energy transition *Energy Policy* **47, Supplement 1** 3–10

Somanathan E, Sterner T, Sugiyama T, Chimanikire D, Dubash NK, Essandoh-Yeddu J, Fifita S, Goulder L, Jaffe A, Labandeira X, Managi S, Mitchell C, Montero J P, Teng F and Zylicz T 2014 National and Sub-national Policies and Institutions *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1141–205

Stanton E A 2010 Negishi welfare weights in integrated assessment models: the mathematics of global inequality *Climatic Change* **107** 417–32

von Stechow C, McCollum D, Riahi K, Minx JC, Kriegler E, van Vuuren DP, Jewell J, Robledo-Abad C, Hertwich E, Tavoni M, Mirasgedis S, Lah O, Roy J, Mulugetta Y, Dubash NK, Bollen J, Ürge-Vorsatz D and Edenhofer O 2015 Integrating global climate change mitigation goals with other sustainability objectives: A synthesis *Annual Review of Environment and Resources* **40** 363–94

Steckel JC, Brecha RJ, Jakob M, Strefler J and Luderer G 2013 Development without energy? Assessing future scenarios of energy consumption in developing countries *Ecological Economics* **90** 53–67

Steckel JC, Edenhofer O and Jakob M 2015 Drivers for the renaissance of coal *Proceedings of the National Academy of Sciences* **112** E3775–81

Steinberger JK and Roberts JT 2010 From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005 *Ecological Economics* **70** 425–33

Szulczewski ML, MacMinn CW, Herzog HJ and Juanes R 2012 Lifetime of carbon capture and storage as a climate-change mitigation technology *PNAS* **109** 5185–9

Tadesse G, Algieri B, Kalkuhl M and von Braun J 2014 Drivers and triggers of international food price spikes and volatility *Food Policy* **47** 117–28

Tavoni M, Kriegler E, Aboumahboub T, Calvin K, De Maere G, Wise M, Klein D, Jewell J, Kober T, Lucas P, Luderer G, McCollum D, Marangoni G, Riahi K and van Vuuren D 2013 The distribution of the major economies' effort in the Durban Platform scenarios *Clim. Change Econ.* **04** 1340009

Tavoni M, Kriegler E, Riahi K, van Vuuren DP, Aboumahboub T, Bowen A, Calvin K, Campiglio E, Kober T, Jewell J, Luderer G, Marangoni G, McCollum D, van Sluisveld M, Zimmer A and van der Zwaan B 2015 Post-2020 climate agreements in the major economies assessed in the light of global models *Nature Clim. Change* **5** 119–26

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C et al. 2009 Beneficial biofuels—The food, energy, and environment trilemma *Science* **325** 270

Ueckerdt F, Hirth L, Luderer G and Edenhofer O 2013 System LCOE: What are the costs of variable renewables? *Energy* **63** 61–75

UNEP 2014 *The Emissions Gap Report 2014: A UNEP Synthesis Report* (Nairobi, Kenya) Online: http://www.unep.org/publications/ebooks/emissionsgapreport2014/

Ürge-Vorsatz D and Tirado Herrero S 2012 Building synergies between climate change mitigation and energy poverty alleviation *Energy Policy* **49** 83–90

Verones F, Hanafiah MM, Pfister S, Huijbregts MAJ, Pelletier GJ and Koehler A 2010 Characterization factors for thermal pollution in freshwater aquatic environments *Environ. Sci. Technol.* **44** 9364–9

van Vliet J, Hof AF, Beltran AM, van den Berg M, Deetman S, den Elzen MGJ, Lucas PL and van Vuuren DP 2013 The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets *Climatic Change* **123** 559–69

van Vuuren DP, Kok M, Lucas PL, Prins AG, Alkemade R, van den Berg M, Bouwman L, van der Esch S, Jeuken M, Kram T and Stehfest E 2015 Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model *Technological Forecasting and Social Change* **98** 303–23

van Vuuren D, Hoogwijk M, Barker T, Riahi K, Boeters S, Chateau J, Scrieciu S, van Vliet J, Masui T, Blok K, Blomen E and Kram T 2009 Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials *Energy Policy* **37** 5125–39

Wada K, Sano F, Akimoto K and Homma T 2012 Assessment of Copenhagen pledges with long-term implications *Energy Economics* **34, Supplement 3** S481–6

Walter A, Dolzan P, Quilodrán O, de Oliveira JG, da Silva C, Piacente F and Segerstedt A 2011 Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects *Energy Policy* **39** 5703–16

Wei M, Patadia S and Kammen DM 2010 Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy policy* **38** 919–31

Weyant JP, de la Chesnaye FC and Blanford GJ 2006 Overview of EMF-21: Multigas mitigation and climate policy *The Energy Journal* **27** 1–32

White JA, Chiaramonte L, Ezzedine S, Foxall W, Hao Y, Ramirez A and McNab W 2014 Geomechanical behavior of the reservoir and caprock system at the In Salah CO_2 storage project *PNAS* **111** 8747–52

Wilson C, Grubler A, Bauer N, Krey V and Riahi K 2013 Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change* **118** 381–95

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith SJ, Janetos A and Edmonds J 2009 Implications of limiting CO_2 concentrations for land use and energy *Science* **324** 1183–6

Wise M, Dooley J, Luckow P, Calvin K and Kyle P 2014 Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century *Applied Energy* **114** 763–73

Woynillowicz D, Severson-Baker C and Raynolds M 2005 *Oil sands fever: The environmental implications of Canada's oil sands rush* (Calgary, Canada: Pembina Institute Edmonton) Online: http://www.pembina.org/pub/203

Zhai H, Rubin ES and Versteeg PL 2011 Water use at pulverized coal power plants with postcombustion carbon capture and storage *Environ. Sci. Technol.* **45** 2479–85

Zickfeld K, Arora VK and Gillett NP 2012 Is the climate response to CO_2 emissions path dependent? *Geophys. Res. Lett.* **39** L05703

7 Synthesis – new insights, challenges and opportunities for mitigation research and global assessment making in a multi-objective context

Carbon dioxide emissions permeate many aspects of modern life, such as housing, mobility as well as production and consumption patterns. Ambitious climate change mitigation pathways with transformational changes thus have considerable implications for broader societal goals and their underlying normative viewpoints. Comprehension of the direct and indirect effects of alternative mitigation pathways as well as their key interdependencies hence cannot be achieved in separate research communities – making mitigation research a particularly interdisciplinary science (see IPCC, 2014).

Yet, at the outset of this PhD project in 2012, academic debates about the interaction between mitigation and SD dimensions were largely confined to specific epistemic communities. In the meantime, it is more widely acknowledged both in science and politics that climate policy cannot be separated any longer from broader SD considerations. In fact, with the establishment of the Sustainable Development Goals (SDGs), mitigation and SD have been firmly integrated. The new challenge for science is to better understand how to realize synergies and minimize trade-offs (see Chapter 6). Accordingly, Hallegatte et al. (2016) argue that "future research – and future IPCC assessments – should help decision-makers harmonize these two agendas and make the long-term climate goal an integral part of the development agenda" (p. 667).

As highlighted in this thesis, global environmental assessments (GEAs) can make important contributions to this integration. Kowarsch et al. (2017, p.3) elaborate on the implications for assessment processes: "the profound multi-dimensionality of the SDGs and the Paris Agreement goals create unprecedented complications for GEAs assessing options for achieving them".[32] In addition, new insights are produced at an unprecedented pace potentially adding to the complexity of the task (Minx et al., 2017b). This highlights questions of how to best synthesize the many new insights and to facilitate an informed public debate so as to enable decision makers to deliver on the implementation of appropriate efforts to meet both climate and SD policy goals.

The different chapters of this thesis not only contribute to new insights how to better integrate the two agendas (see section 7.1 for a summary). They also discuss challenges and opportunities ahead if this surge in knowledge on the interaction of mitigation and SD is to be made useful for decision-making by means of scientific assessments (see section 7.2). Section 7.3 points to opportunities from innovative synthesis tools for global assessments, provides an outlook to future mitigation and SD research and discusses to what extent the IPCC mandate may need to be adapted against the background of developments in the scientific landscape and international climate policy.

[32] The diversity of actors, plausible assumptions and normative viewpoints makes a consensus on appropriate action to address climate change virtually impossible (Kowarsch et al., 2017). But contrary to conventional thinking, consensus is not a precondition for sound scientific policy advice (Oreskes, 2004a,b) and GEAs are an important tool to reconcile disparate views (see Chapter 2).

7.1 Insights for global assessment making

As set out in the introduction, this thesis is concerned with two core research questions:

i) How to assess and synthesize diverse strands of mitigation literature for policymakers in a *comprehensive, objective* and *balanced* way?

ii) How to embed the mitigation research in a *broader SD context* and what are the main *challenges* and *opportunities* encountered when doing so?

The previous chapters jointly highlight that the two questions are inextricably interlinked:

Putting mitigation choices into a *broader SD context* enhances the *objectivity* of assessing alternative mitigation pathways as this avoids neglecting the effects on a diverse set of other SD objectives beyond climate goals. It also makes scientific policy advice more relevant as side-effects of climate policies in non-climate dimensions often shape public acceptance of particular pathways (see Chapters 5 and 6). At the same time, *comprehensively* assessing future climate policy choices in a multi-objective setting necessarily needs to draw on diverse strands of literature in a *balanced* way – raising questions around possible ways of knowledge aggregation and synthesis when complexity grows. This thesis offers some important insights and offers a glimpse into the future *challenge*s of and *opportunities* from synthesizing mitigation research in the context of SD.

Based on a reflection of the science-policy interface, Chapter 1 characterizes climate change as a “wicked” public policy problem: With the controversies about appropriate short-term climate action and their underlying value dissent (see also Kowarsch et al., 2016; Pielke, 2007) as well as the complex long-term implications, mitigation research is both a prime example for the challenges of deep uncertainty (Funtowicz and Ravetz, 1993) and for the promise of assessment making (see section 1.1).

While the institutional and political constraints to comprehensively assess the available knowledge (Edenhofer and Minx, 2014) have led to controversies about the objectivity and balance of past assessments (Cash et al., 2003; Keller, 2009; Mitchell et al., 2006), this thesis argues that taking an even broader SD perspective on the climate policy problem is crucial for understanding the risks and co-benefits of alternative mitigation pathways across multiple policy fields, socioeconomic contexts as well as spatial and temporal scales. In the same vein, Kowarsch et al. (2017, p.3 and Annex 8.3) argue that appreciation of co-benefits and risks “is crucial for managing these wicked problems”.

Chapter 2 stresses that the short-term ambition of climate policy is crucial as it largely determines the characteristics of mid- and long-term greenhouse gas (GHG) emissions pathways required to stay (well) below 2°C of global warming: Any further delay in ambitious mitigation efforts reduces the mid- to long-term flexibility to choose between low-carbon energy technologies and their associated co-effects in other SD dimensions. The viewpoints on related risk trade-offs differ across locally specific contexts with varying priority settings and risk perceptions and need to be taken into account in climate policy decisions. Building on the PEM (see Edenhofer and Kowarsch, 2015), it is argued that the role of science is to facilitate an informed public debate about such risk trade-offs and a robust decision by policy makers on alternative mitigation pathways.

This was attempted in IPCC AR5 for the case of the 2°C limit. While it serves as a useful reference point for tracking progress at the global level, its operationalization on the local and national level is challenging as short-term entry points into decision making need to be identified that offer benefits beyond the reduced long-term climate impacts globally. While Chapter 2 offers some hints to promising research areas, the following chapters in this thesis argue in some more detail for and contribute to developing a better understanding of the various SD implications of important mitigation options and innovative ways of presenting them in global assessments to help better characterize the decision problems that policy makers face.

Chapter 3 analyzes the example of bioenergy as a key mitigation option where disagreements around the SD implications – rooted in deep uncertainties and value dissent – have been particularly heated. Given the diverging spatial and temporal scales on which bioenergy co-effects could materialize, bioenergy technologies are particularly apt to pinpoint the challenges and opportunities of comprehensively assessing results from different scientific communities and of understanding (if possible, reconciling) disparate views that are often buried in the different research communities' methods, assumptions and normative viewpoints. While some progress has been made for integrating the different insights, the chapter concludes that much work still lies ahead to better understand the sources and causes of result variation. This would include identifying alternative future bioenergy deployment levels for which the underlying assumptions are made more transparent across many strands of literature.

More consolidated knowledge would be very relevant given the high reliance of ambitious mitigation pathways (particularly for 1.5°C pathways) on BECCS and other land-based negative emission technologies (NETs) (Fuss et al., 2014; IPCC, 2018; Rogelj et al., 2015). Given the highly diverging SD risks of NETs (Smith et al. 2016) and the rapidly increasing knowledge base (Minx et al., 2017b) it remains to be seen if the prospect of NETs eventually increases or narrows the option space for climate action (Anderson and Peters, 2016). But the contested role of bioenergy highlights the urgency to develop a better conceptual understanding of evaluating multiple SD effects of mitigation choices on different spatial and temporal scales in a coherent way.

Given the scarcity of conceptual work on the linkage between SD outcomes and social welfare effects (Mattauch et al., 2015), Chapter 4 does a first step in providing a more holistic welfare perspective on the interactions of climate and other SD policies that can provide a basis for linking (and, if possible, reconciling) different literature strands and underlying methods, assumptions and normative viewpoints. The chapter stresses the importance of jointly analysing the multiple interacting local, national and regional SD policy instruments partly addressing existing externalities. Particularly in the absence of a global carbon price anywhere near its optimal level (Jakob and Steckel, 2016), such second-best analysis is a precondition for understanding implications for social welfare.

With a view to locally specific policy contexts, risk perceptions and priority settings, social welfare accounting in such a multi-objective context is extremely challenging but offers the promise to maximize synergies and minimize potential (risk) trade-offs across mitigation and other SD dimensions. Given that the adoption of the SDGs will spark a lot more research in a multi-objective context (Jakob and Steckel, 2016; Janetschek et al., 2018; McCollum et al., 2018; Nilsson et al., 2016), developing a common language and unifying frameworks on which assessment can rely is key to synthesize this surge in knowledge and to bring together deeply interdisciplinary research fields.

As a first step, Chapter 5 develops a simple conceptual framework for mapping the different literature strands on the interaction of mitigation and SD policies and measures and reviews their respective contributions to a more holistic understanding of their social welfare effects. The chapter argues that there is a trade-off between the number of objectives analyzed and the ability to present quantitative results, particularly for overall welfare implications on a global scale. But the chapter also shows the potential for further synthesis when combining quantitative and qualitative information, drawing on the respective strengths of the different research communities.

While further extending the system boundaries and integrating more modules in a single model framework can also offer key insights despite the methodological challenges associated with the growth in complexity, synthesizing increasingly diverse strands of literature is not possible without additional tools for assessment making (Minx et al., 2017b). For example, the chapter argues for adopting a risk perspective where cost-benefits analysis is no longer possible given the multiple fat-tailed risks (cf. Kunreuther et al., 2013) to inform public debates and help policy makers choose among alternative mitigation pathways and the related effects in other SD dimensions.

As a proof of concept in analyzing alternative 2°C pathways in multiple other SD dimensions, Chapter 6 draws on a series of scenarios from leading global integrated energy-economy-climate models (Kriegler et al., 2014; Riahi et al., 2014) and identifies a set of indicators that can be linked to short- and mid-term effects on energy-related SDGs. Based on graphical representation tools, the chapter can show both intuitive and unintuitive effects from the choice of alternative mitigation pathways on a set of SD risks. With this innovative approach, the chapter makes some of these effects more transparent in one figure at one glance. In this way, Chapter 6 can also reveal over-simplistic arguments about the non-feasibility of particular pathways (Anderson, 2015) and link near-term climate policy choices to longer-term SD implications.

The chapter also highlights the increasing risks of delaying ambitious short-term climate policies for achieving many SDGs. Similarly, it makes the risk trade-offs across key SD dimensions transparent if some of the key mitigation technologies are only available to a limited extent (e.g. bioenergy). Confirming results from Chapter 5, it points to the decrease in SD risks across all dimensions if lower-than-projected energy demand growth can be realized. Again, this chapter highlights the added value of greater efforts to aggregate and synthesize existing knowledge for facilitating a balanced public debate and informing robust decision making.

Chapters 5 and 6 show the untapped potential that increasing data availability and the knowledge surge could contribute to a more objective, comprehensive and balanced assessment to facilitate deliberative learning on climate policy alternatives in the light of their interlinkages with SDGs. While some indicators are rough representations of the underlying SD dimensions, more robust scenario results are underway, e.g. for the food-water-energy nexus (Obersteiner et al., 2016; Riahi et al., 2017) and model teams are collaborating (with contributions from the candidate) to better map indicators to SDGs.

The thesis highlights the importance of looking at alternative mitigation pathways in a multiple-indicator space as a pre-condition for an informed public debate on climate policy choices. That, however, implies further increasing complexity in a research field that is expanding so rapidly that no individual can review all relevant publications (Minx et al., 2017b). Section 7.2 thus discusses the rising complexity due to the proliferation of objectives and the challenges related to the volume, velocity and variety of new knowledge creation on climate change (cf. Minx et al., 2017a) and SD.

7.2 Challenges for global assessment making

The exponential growth in the climate change literature further aggravates the challenges for GEAs beyond uncertainties, increasing complexity and value dissent. Today, every year more than 30,000 new publications are added to the body of evidence in the field of climate change listed only in the Web of Science (WoS) (Haunschild et al., 2016; Minx et al., 2017b). This is larger than the entire climate change literature before 2001 – comprising three IPCC assessments (see Figure 7.1, left panel).[33] Unsurprisingly, the share of publications that can be directly considered in climate change assessments has steadily declined over time (see Figure 7.1, right panel). The implication is that there is a fast-growing risk of publication selection bias in GEAs. Assessment-making has thus become a challenge of dealing with 'big literature' (see Nunez-Mir et al., 2016).

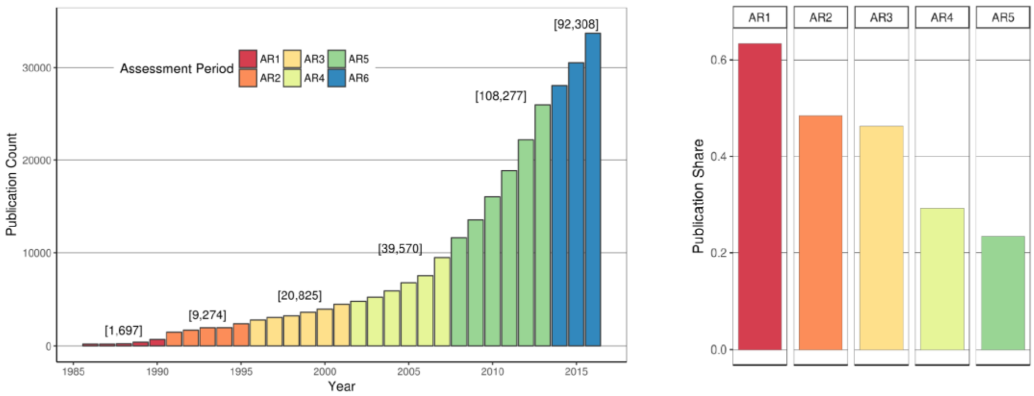

Figure 7.1 Left panel: Total number of scientific publications on climate change between 1986 and 2015 as listed in the Web of Science (WoS): exponential growth without a clear indication of levelling out. The six IPCC assessment cycles are identified by different colours. Right panel: The ratio of unique reference counts in each IPCC report to the number of new publications on climate change during the respective assessment cycle as listed in the WoS. The direct coverage of the emerging literature in IPCC reports has been declining rapidly. Used with permission of Elsevier, from Minx et al. (2017a) Learning about climate change solutions in the IPCC and beyond, *Environ. Sci. Policy* 77, 252–259.

[33] These numbers are substantial but only include literature found in WoS and neglect a substantial number of sources eligible for IPCC and other assessments. Moreover, there is a large amount of literature that does not focus on climate change, but is assessment-relevant, such as literature on various relevant aspects of human behaviour, e.g. cooperation, behavioural responses to different types of policies or risk perception.

While more knowledge can help to further clarify existing uncertainties and to prioritize possible ways forward for global assessment making, the big challenge and opportunity is to effectively harness the new insights continuously generated. At the current growth rate of knowledge creation, however, even large-scale assessment processes, such as the IPCC, are not (yet) designed to deal with this massive challenge.

The IPCC is hence at a bifurcation, if the mandate to provide comprehensive, objective and balanced assessments is still to be taken seriously. On the one hand, this thesis argues that a comprehensive global assessment of alternative mitigation pathways in a multi-objective context needs to consider a wider set of research communities, methodological approaches, assumptions and normative viewpoints. On the other hand, further extending the system boundaries across different policies fields, socioeconomic contexts as well as spatial and temporal scales to make co-benefits, unintended consequences and value judgements more transparent – as demanded by the PEM – potentially makes assessments even more infeasible in the age of big literature.

A recent study by Elsevier, for example, identified a current output in the field of sustainability sciences of almost 80,000 per year (Elsevier, 2015) dwarfing the number of publications on climate change. Accordingly, the total amount of studies published on keywords linked to both 'sustainability' and 'climate change mitigation' tripled from 2012 to 2016 to reach a total number of 4452 references (see Figure 7.2). While literature on the interaction between mitigation and SD was still negligible for the first three IPCC assessments, about 2000 studies relevant for AR6 have already been published in the few years since AR5[34], rapidly expanding the boundaries of existing knowledge on the interaction between mitigation and SD.

If the general keyword term 'sustainab*' is replaced by the union of keywords related to sub-areas of SD, such as those used in Chapter 5, Figure 5.3, the challenge seems to be even more substantial (see Table 7.1). Following the approach taken by Grieneisen and Zhang (2011), a collection of relevant keyword terms can be identified for some of the most researched SD sub-areas, drawing on a number of bibliometric studies in the field:

i) Hassan et al. (2013) in the case of biodiversity and water,
ii) Xie et al. (2008) and Zhang et al. (2009) for the case of air quality and health and
iii) a conceptual paper on defining energy security (Cherp and Jewell, 2014).

Considering those publications that contain relevant terms in their title, abstract and keywords related to both mitigation and SD sub-areas, the number of relevant publications increases from 4452 to 7390 despite the fact that many other sub-areas have not even been considered by the WoS query used here. Without additional innovations in the way new knowledge is synthesized, this seems to be a daunting task.

[34] For comparison, WGIII AR5 covered over 1000 references (with over 750 journal articles) in the sections relevant for SD while 2320 studies were published on the interaction between mitigation and SD by the literature cut-off date (3 October 2013) according to the WoS query used here (see Table 7.1 and the Annex section 8.1). Even though these sets of references may not entirely overlap, comparing this to an average ratio of about 20% (see Figure 7.1, right panel), this literature base still seems to have been comparatively well represented in the WGIII AR5.

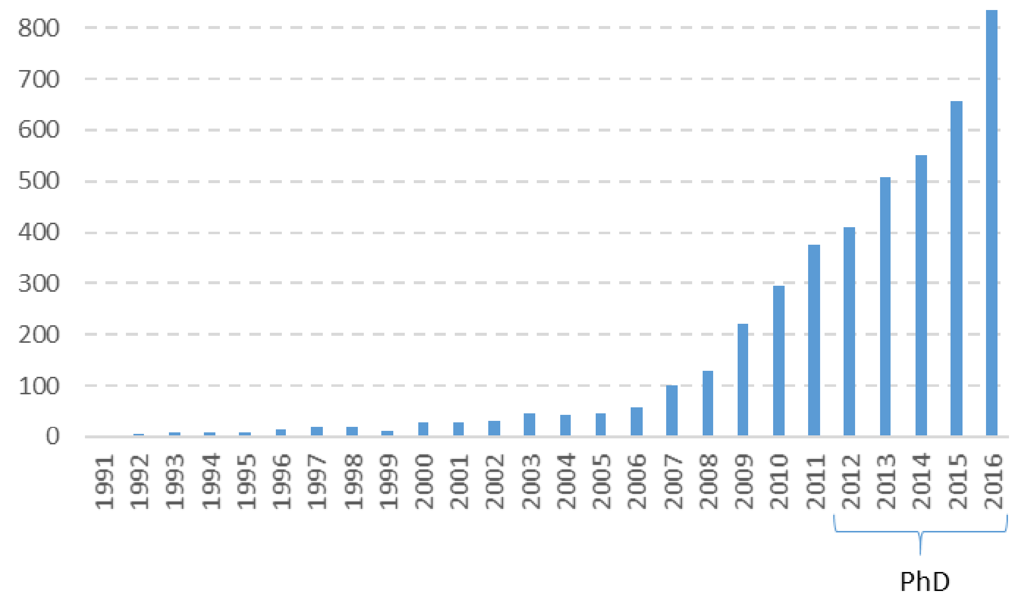

Figure 7.2 Scientific literature record count as listed in the Web of Science published since 1991 which contain terms in their title, abstract or keywords associated with the concepts 'sustainability' and 'climate change mitigation' (see details on the queries used in the Annex section 8.1).

If the number of annual publications does not level out, traditional reviews, for instance, will be increasingly inadequate to aggregate and synthesize the new knowledge. For example, the allowable number of references in *Annual Review of Environment and Resources* was 150 in the case of Chapter 5, which was barely enough to cover the 50 most important integrated model publications on the interaction between mitigation and six SD sub-areas (see section 5.4) – representing two thirds of the available literature with a global focus at that point in time (see Table 7.1). Table 7.1 shows, however, that the amount of publications on the interaction between mitigation and SD sub-areas without an explicit focus on IAMs is nearly two orders of magnitude higher. Even larger author teams would not be able to review that many new insights. Without further conceptual and methodological innovations in integrating knowledge and synthesizing insights, the limits to deliberative learning process about policy alternatives in the field of mitigation and sustainability research will soon become apparent.

Table 7.1 Scientific literature as listed in the Web of Science which contain terms in their title, abstract or keywords associated with 'climate change mitigation' and one of the SD sub-areas 'air pollution', 'energy security', 'biodiversity' and 'water' (1991-2016, see details on the queries in the Annex 8.1).

Number of WoS references on…	air quality and health	energy security	biodiversity	water	any of them
	191591	10886	177295	468356	821124
climate change (274438) and…	8672	1898	20197	37817	64156
mitigation (45976) and…	2438	816	1635	3132	7390
IAMs (11609) and…	279	72	277	1415	1940
mitigation and IAMs (812)	76	39	32	71	190
of which published before Ch. 5	50	23	22	41	120
of which relevant for Ch. 5	29	15	7	11	55
of which with global focus	16	11	5	10	36
of which reviewed for Ch. 5	11	11	0	4	24
papers cited not included above	18	15	1	5	39

7.3 Opportunities for global assessment making – outlook to future mitigation and sustainability research

Following Minx et al. (2017b) and Kowarsch (2016), several innovations could safeguard an assessment process apt for this challenge: In analogy to 'big data', solutions to deal with 'big literature' are suggested along three V's – volume, velocity, and variety – that divide the challenge associated with the surge in new knowledge into three components:

i) *Volume* refers to the immense size of the literature body that is growing beyond individual scientists' comprehension – for both climate change and sustainability research. This calls for computer-assisted assessments that utilize big-data methods in order to convincingly ensure a *comprehensive* consideration of the range of research results (see Ford et al., 2016 for research on adaptation to climate change). Corpus linguistic tools (e.g. Blei et al., 2003; Lamb et al., 2018; Minx et al., 2017b) from computational linguistics and other big data applications can help here to enable an understanding of a literature landscape that can no longer be manually traced. Hence, big data applications need to be explored to ensure transparency and credibility of GEAs in the future.

ii) *Velocity* refers to the large number of new publications every year with new scientific insights to be integrated into current understanding of climate change and sustainability research. It implies that research may be increasingly quickly outdated. This highlights the importance of research synthesis as part of everyday scientific practice (such as evidence maps that can help to collect and categorize studies, cf. McKinnon et al., 2015) and for assessments to aggregate and synthesize new insights in an *objective* way. Chapters 3, 4 and 5, for example, can be considered pre-assessments (Kowarsch et al., 2017).

iii) *Variety* refers to the notion that academic fields and results are getting increasingly diverse. This emphasizes the importance of meta-analytical research as a formal research activity on research results to shed light on what explains variation and of the challenge of assessments to ensure a *balanced* consideration of disparate viewpoints. Chapters 3 and 5, for example, aim at better understanding result variation across different research communities and sets of assumptions. More formal ways of systematic reviews and meta-analyses, drawing on established methods in other fields (Petticrew and McCartney, 2011), and visualization tools for multi-dimensional data, such as performed in Chapter 6, urgently need to be acknowledged as research in its own right.

If these three V's can be addressed, the big literature challenge might become an opportunity to progress more rapidly and reduce uncertainties over time. This could turn the size and growth of the literature less relevant and the broadening of climate change policies to include SD considerations into an opportunity. This becomes particularly relevant as important methods such as CBA and expected value theory, although workhorses for other public policy problems, reach the limits of their applicability, particularly in a multi-objective context (see Chapter 4), giving way to (as of now) less formalized approaches such as multi-criteria assessment (see Chapter 5) and risk management analysis (see Chapter 6; Drouet et al., 2015; Kunreuther et al., 2013).

To facilitate deliberative learning process among all actors involved via a rationale public debate and inform evidence-based decision making on coherent future policy pathways, the insights of this thesis call for a new science of assessment making that is:

i) truly interdisciplinary, aggregating and synthesizing insights on technical, economic, political, ethical and social aspects with innovative assessment tools,
ii) globally connected, drawing on fragmented knowledge across research communities with a diverse set of underlying assumptions, methods and worldviews, and
iii) mindful of locally specific socioeconomic contexts, taking into account diverging risk perceptions and priority settings.

Along these lines, the previous chapters put forward several recommendations that can help to deliver on the promise of assessment making and provide key building blocks to a new science of assessment making:

i) synthesizing SD implications of mitigation at the local/national scale to better map to decision-making jurisdictions and the respective risk perceptions and priority settings, possibly motivating early action (see Chapters 2 and 5 and McCollum et al., 2018);
ii) integrating results from additional research communities into global assessments, such as human geography and other relevant social sciences to foster a rich problem understanding (see Chapter 3 and Victor, 2015);
iii) characterizing alternative welfare functions that better allow for dealing with different priority settings across and within regions with respect to the diverse set of SD objectives, particularly in developing countries (see Chapters 4 and 5);
iv) developing a multidimensional typology of co-effects on SD dimensions beyond the categorization into sectors and sustainability aspects to better communicate the linkages of SD goals across different locations and inform the choice of methods, models, and system boundaries as well as priority settings in the policy process to tackle multiple objectives (see Chapter 5);
v) agreeing on common metrics and alternative ambition levels for a set of other SDGs (analogue to GHG concentration goals) to better facilitate synthesis across different strands of literature and monitor global risk-risk trade-offs (see Chapters 5 and 6) – if possible (given data availability issues) and useful (given context-specific circumstances, cf. McCollum et al. 2018).

On top of these recommendations for improving the SPI on the interaction of mitigation and SD, some insights from this thesis are also relevant for discussions on the future of the IPCC (see, e.g. Carraro et al., 2015; Edenhofer and Minx, 2014).[35] This is particularly relevant, since future IPCC assessment results will have a very direct way into the UNFCCC negotiation rooms via the Global Stocktake (GST): As set out in Art. 14 of the

[35] Cf. the thirty-ninth session of the IPCC on the Future of the IPCC in Berlin, Germany, April 2014.

Paris Agreement, the GST is supposed to assess the collective progress towards achieving its purpose and its long-term goals as well as to inform further individual actions by Parties in the light of equity and the best available science.

The first GST will happen in 2023 and every five years thereafter.[36] With the IPCC reports identified as a source of input to the GST[37], different ideas are being considered around aligning IPCC assessment cycles which typically last for six to seven years – either by shortening or extending assessment cycles and adapting IPCC products with the goal to effectively feed into the UNFCCC process (see Carraro et al., 2015). Since such changes would require amendments to the IPCC procedures, this discussion should be used as an opportunity to rethink the mandate of the IPCC against the context of the surge in relevant literature and increased expectations for an integrated assessment of mitigation and SD research as implicit in the Paris Agreement.

While the detailed modalities of the GST are still being discussed among UNFCCC Parties in the Ad-Hoc Working Group on the Paris Agreement (APA), three tentative takeaways from the negotiations are particularly relevant in this context:

i) the GST should assess the progress across all long-term goals of the Paris Agreement requiring information on SD including SDGs;
ii) the sources of input discussed include but are not limited to the IPCC assessment results; and
iii) the information needs to be presented in a way appropriate to assess the collective implementation and/or progress.

For each of these issues under discussion, this thesis provides relevant insights that should be considered when discussing the future of the IPCC:

The IPCC mandate needs to better reflect the SDG agenda with respect to report space and number of authors devoted to the assessment of relevant research. In the AR5 Working Group III (WGIII), the focus of the IPCC mandate on mitigation – rather than SD more broadly – led to a limited number of experts among the Lead Authors and to a limited writing space on mitigation-SD interactions (about 6%). This will not be enough in AR6 if the IPCC aims at assessing mitigation research in a wider SD context in a comprehensive, objective and balanced way. The IPCC should also aim at more flexibility for its assessment products. The preparation of the IPCC Special Report on Global Warming of 1.5°C as an input to the 2018 Talanoa Dialogue is a good example as both mitigation risks and co-benefits will be higher in 1,5°C pathways relative to less ambitious climate policy pathways (IPCC, 2018).

To stay relevant, the IPCC needs to increase the solution-orientation of its assessments (see Figure S-8.1 in Annex 8.3). This could be achieved through rearranging the focus of the three IPCC WGs so as to provide scientific advice how to respond to mitigation and adaptation challenges in an integrated way. For sustainable infrastructure planning, for example, governments are expected to incentivize low-carbon development pathways

[36] http://unfccc.int/meetings/paris_nov_2015/items/9445.php
[37] Decision 1/CP.21, paragraphs 99(b).

while, at the same time, improving adaptive capacity and inclusive access (Bak et al., 2017). National planning processes, such as the NDCs and national adaptation and disaster risk planning also need to be better integrated (Hammill and Price-Kelly, 2017). With its current structure of WGs, the IPCC is not likely to serve the needs of governments.

The IPCC and the scientific community at large have to cope with the challenge that the three long-term goals of the Paris Agreements lend themselves to a varying degree to be tracked globally. While one ton of GHG emissions avoided has the same global mitigation outcome irrespective of the location, adaptation outcomes are context-specific and their quantitative aggregation in a global metric is misguiding at best (see Adger et al., 2005; Ford and Berrang-Ford, 2016; Leiter and Pringle, 2018). This insight is very similar to those from this thesis on the limits of quantifying and aggregating the co-benefits of mitigation for SD outcomes (see Chapter 5). This stresses the caution that needs to be in place to avoid undue politization by quantifying and aggregating information that should rather be assessed in its particular context or in qualitative terms (see also McCollum et al., 2018).

By spelling out the most important challenges of mitigation research in the context of SD, and pointing to a number of opportunities for improving future assessment making in terms of the process and content, the candidate hopes to have contributed to a learning exercise necessary for a better integration of mitigation research and sustainability science and its synthesis for fostering deliberative learning processes and public debates as well as improving decision-making in the field of climate change and beyond.

7.4 References

Anderson, K., 2015. Duality in climate science. *Nat. Geosci.* 8, 898–900. https://doi.org/10.1038/ngeo2559
Anderson, K., Peters, G., 2016. The trouble with negative emissions. *Science* 354, 182–183. https://doi.org/10.1126/science.aah4567
Bak, C., Bhattacharya, A., Edenhofer, O., Knopf, B., 2017. Towards a comprehensive approach to climate policy, sustainable infrastructure, and finance. *Econ. Open-Access Open-Assess. E-J. Special Issue: the Sustainable Development Goals—Assessing Interlinkages, Trade-offs and Synergies for Policy Design*. https://doi.org/10.5018/economics-ejournal.ja.2017-33
Blei, D.M., Ng, A.Y., Jordan, M.I., 2003. Latent Dirichlet Allocation. *J. Mach. Learn. Res.* 3, 993–1022.
Carraro, C., Edenhofer, O., Flachsland, C., Kolstad, C., Stavins, R., Stowe, R., 2015. The IPCC at a crossroads: Opportunities for reform. *Science* 350, 34–35. https://doi.org/10.1126/science.aac4419
Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci.* 100, 8086–8091. https://doi.org/10.1073/pnas.1231332100
Cherp, A., Jewell, J., 2014. The concept of energy security: Beyond the four As. *Energy Policy* 75, 415–421. https://doi.org/10.1016/j.enpol.2014.09.005
Drouet, L., Bosetti, V., Tavoni, M., 2015. Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nat. Clim. Change* 5, 937–940. https://doi.org/10.1038/nclimate2721
Edenhofer, O., Kowarsch, M., 2015. Cartography of pathways: A new model for environmental policy assessments. *Environ. Sci. Policy* 51, 56–64. https://doi.org/10.1016/j.envsci.2015.03.017
Edenhofer, O., Minx, J., 2014. Mapmakers and navigators, facts and values. *Science* 345, 37–38. https://doi.org/10.1126/science.1255998
Elsevier, 2015. *Sustainability Science in a Global Landscape*. Online: https://www.elsevier.com/about/corporate-responsibility/sustainability-science-in-a-global-landscape
Ford, J.D., Berrang-Ford, L., 2016. The 4Cs of adaptation tracking: consistency, comparability, comprehensiveness, coherency. *Mitig. Adapt. Strateg. Glob. Change* 21, 839–859. https://doi.org/10.1007/s11027-014-9627-7
Ford, J.D., Tilleard, S.E., Berrang-Ford, L., Araos, M., Biesbroek, R., Lesnikowski, A.C., MacDonald, G.K., Hsu, A., Chen, C., Bizikova, L., 2016. Opinion: Big data has big potential for applications to climate change adaptation. *Proc. Natl. Acad. Sci.* 113, 10729–10732. https://doi.org/10.1073/pnas.1614023113
Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. *Futures* 25, 739–755. https://doi.org/16/0016-3287(93)90022-L
Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. *Nat. Clim. Change* 4, 850–853. https://doi.org/10.1038/nclimate2392
Grieneisen, M.L., Zhang, M., 2011. The current status of climate change research. *Nat. Clim. Change* 1, 72–73. https://doi.org/10.1038/nclimate1093
Hallegatte, S., Rogelj, J., Allen, M., Clarke, L., Edenhofer, O., Field, C.B., Friedlingstein, P., van Kesteren, L., Knutti, R., Mach, K.J., Mastrandrea, M., Michel, A., Minx, J., Oppenheimer, M., Plattner, G.-K., Riahi, K., Schaeffer, M., Stocker, T.F., van Vuuren, D.P., 2016. Mapping the climate change challenge. *Nat. Clim. Change* 6, 663–668. https://doi.org/10.1038/nclimate3057

Hammill, A., Price-Kelly, H., 2017. *Using NDCs, NAPs and the SDGs to Advance Climate-Resilient Development., Expert Perspective for the NDC Partnership*. NAP Global Network, International Institute for Sustainable Development (IISD), Winnipeg, Canada. Online: https://napglobalnetwork.org/resource/using-ndcs-naps-sdgs-advance-climate-resilient-development/

Hassan, S.-U., Haddawy, P., Zhu, J., 2013. A bibliometric study of the world's research activity in sustainable development and its sub-areas using scientific literature. *Scientometrics* 99, 549–579. https://doi.org/10.1007/s11192-013-1193-3

Haunschild, R., Bornmann, L., Marx, W., 2016. Climate Change Research in View of Bibliometrics. *PLOS ONE* 11, e0160393. https://doi.org/10.1371/journal.pone.0160393

IPCC, 2018. *Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jakob, M., Steckel, J.C., 2016. Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.* 11, 104010. https://doi.org/10.1088/1748-9326/11/10/104010

Janetschek, H., Brandi, C., Keijzer, N., Scholz, I., 2018. Thematic connections of the Paris climate agreement and the 2030 Agenda, in: OECD (Ed.), *Policy coherence for sustainable development 2018: towards sustainable and resilient societies.* OECD Publishing, Paris, France, pp. 217–220.

Keller, A.C., 2009. Credibility and Relevance in Environmental Policy: Measuring Strategies and Performance among Science Assessment Organizations. *J. Public Adm. Res. Theory* 20(2), 357–386. https://doi.org/10.1093/jopart/mup001

Kowarsch, M., 2016. Policy assessments to enhance EU scientific advice. *Nat. Clim. Change* 6, 15–17. https://doi.org/10.1038/nclimate2835

Kowarsch, M., Garard, J., Riousset, P., Lenzi, D., Knopf, B., Harrs, J.-A., Edenhofer, O., 2016. Scientific assessments to facilitate deliberative policy learning. *Palgrave Commun.* 2, 16092. https://doi.org/10.1057/palcomms.2016.92

Kowarsch, M., Jabbour, J., Flachsland, C., Kok, M.T.J., Watson, S.R., Haas, P.M., Minx, J.C., Alcamo, J., Garard, J., Riousset, P., Pintér, L., Langford, C., Yamineva, Y., von Stechow, C., O'Reilly, J., Edenhofer, O., 2017. A roadmap for global environmental assessments. *Nat. Clim. Change* 7, 379–382. https://doi.org/10.1038/nclimate3307

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P., P. van Vuuren, D., Edenhofer, O., 2015. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change* 90, Part A, 24–44. https://doi.org/10.1016/j.techfore.2013.09.021

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C.B., Yohe, G., 2013. Risk management and climate change. *Nat. Clim. Change* 3, 447–450. https://doi.org/10.1038/nclimate1740

Lamb, W.F., Callaghan, M.W., Creutzig, F., Khosla, R., Minx, J.C., 2018. The literature landscape on 1.5°C climate change and cities. *Curr. Opin. Environ. Sustain., Environmental change assessment* 30, 26–34. https://doi.org/10.1016/j.cosust.2018.02.008

Leiter, T., Pringle, P., 2018. Pitfalls and potential of measuring climate change adaptation through adaptation metrics, in: Christiansen, L. (Ed.), *Perspectives Series on Metrics for Climate Change Adaptation*. UNEP DTU Partnership, Copenhagen, Denmark.

Mattauch, L., 2015. *Rent and Redistribution: The welfare implications of financing low-carbon public investment* (PhD thesis). Technische Universtität, Berlin. Online: https://depositonce.tu-berlin.de/bitstreams/8cb491ff-db27-460b-969f-05de3aff68cb/download

McCollum, D.L., Echeverri, L.G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., Krey, V., Minx, J.C., Nilsson, M., Stevance, A.-S., Riahi, K., 2018. Connecting the Sustainable Development Goals by their energy inter-linkages. *Environ. Res. Lett.* 13, 033006. https://doi.org/10.1088/1748-9326/aaafe3

McKinnon, M.C., Cheng, S.H., Garside, R., Masuda, Y.J., Miller, D.C., 2015. Sustainability: Map the evidence. *Nature* 528, 185–187. https://doi.org/10.1038/528185a

Minx, J.C., Callaghan, M.W., Garard, J., Edenhofer, O., 2017a. Learning about climate change solutions in the IPCC and beyond. *Environ. Sci. Policy* 77, 252–259. https://doi.org/10.1016/j.envsci.2017.05.014

Minx, J.C., Lamb, W.F., Callaghan, M.W., Bornmann, L., Fuss, S., 2017b. Fast growing research on negative emissions. *Environ. Res. Lett.* 12, 035007. https://doi.org/10.1088/1748-9326/aa5ee5

Mitchell, R.B., Clark, W.C., Cash, D.W., Dickson, N.M. (Eds.), 2006. Global Environmental Assessments: Information and Influence. MIT Press, Cambridge, MA, USA.

Neil Adger, W., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. *Glob. Environ. Change, Adaptation to Climate Change: Perspectives Across Scales* 15, 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Nilsson, M., Griggs, D., Visbeck, M., 2016. Policy: Map the interactions between Sustainable Development Goals. *Nat. News* 534, 320. https://doi.org/10.1038/534320a

Nunez-Mir, G.C., Iannone, B.V., Pijanowski, B.C., Kong, N., Fei, S., 2016. Automated content analysis: addressing the big literature challenge in ecology and evolution. *Methods Ecol. Evol.* 7, 1262–1272. https://doi.org/10.1111/2041-210X.12602

Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S., van Vuuren, D., 2016. Assessing the land resource–food price nexus of the Sustainable Development Goals. *Sci. Adv.* 2(9). https://doi.org/10.1126/sciadv.1501499

Oreskes, N., 2004a. Science and public policy: What's proof got to do with it? *Environ. Sci. Policy, Science, Policy, and Politics: Learning from Controversy Over The Skeptical Environmentalist* 7, 369–383. https://doi.org/10.1016/j.envsci.2004.06.002

Oreskes, N., 2004b. The Scientific Consensus on Climate Change. *Science* 306, 1686–1686. https://doi.org/10.1126/science.1103618

Petticrew, M., McCartney, G., 2011. Using systematic reviews to separate scientific from policy debate relevant to climate change. *Am. J. Prev. Med.* 40, 576–578. https://doi.org/10.1016/j.amepre.2010.12.022

Pielke, R.A.J., 2007. *The Honest Broker: Making Sense of Science in Policy and Politics.* Cambridge University Press.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D.L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., Edenhofer, O., 2015. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* 90, Part A, 8–23. https://doi.org/10.1016/j.techfore.2013.09.016

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K., 2015. Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nat. Clim. Change* 5, 519–527. https://doi.org/10.1038/nclimate2572

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Change* 6, 42–50. https://doi.org/10.1038/nclimate2870

Victor, D., 2015. Climate change: Embed the social sciences in climate policy. *Nat. News* 520, 27. https://doi.org/10.1038/520027a

Xie, S., Zhang, J., Ho, Y.-S., 2008. Assessment of world aerosol research trends by bibliometric analysis. *Scientometrics* 77, 113–130. https://doi.org/10.1007/s11192-007-1928-0

Zhang, G., Xie, S., Ho, Y.-S., 2009. A bibliometric analysis of world volatile organic compounds research trends. *Scientometrics* 83, 477–492. https://doi.org/10.1007/s11192-009-0065-3

8 Annex

8.1 Keywords for the analysis of the surge in climate and SD research

To study the literature growth in the field of climate and SD research, scientometric methods were employed for the Web of Science (WoS) database that provides a wide range of peer-reviewed articles, books and conference proceedings across disciplines. As a subscription-based indexing service WoS provides a relatively comprehensive search of peer-reviewed scientific citations (Minx et al. 2017). The query used to find the number of publications in the period between 1991 and 1016 in the WoS online database related to the topics ‘climate’, ‘climate change mitigation’, ‘IAMs’, ‘Air quality and health’, ‘energy security’, ‘biodiversity’, and/or ‘water’ consisted of a set of keywords, taken from bibliometric studies. The respective lists of keywords are shown below some of which have been stemmed to take into account many words with the same root. Some keywords which have field-specific meanings in climate or sustainability science can have additional meanings in other fields, so these are ‘‘ANDed’’ with ‘climat*’ or ‘sustainabl*’ to restrict their meaning. In addition, some keywords are ‘‘ANDed’’ with a set of source titles in order to limit the scope of publications in the sub-area.

Climate (keywords taken from Grieneisen and Zhang 2011)

SO = (Climate Alert OR Climate Dynamics OR Climate Policy OR Climatic Change OR Global and Planetary Change OR Global Change Biology OR International Journal of Greenhouse Gas Control OR Mitigation and Adaptation Strategies for Global Change) OR TS = (((CO2 OR "carbon dioxide" OR methane OR CH4 OR "carbon cycle" OR "carbon cycles" OR "carbon cycling" OR "carbon budget*" OR "carbon flux*" OR "carbon mitigation") AND (climat*)) OR (("carbon cycle" OR "carbon cycles" OR "carbon cycling" OR "carbon budget*" OR "carbon flux*" OR "carbon mitigation") AND (atmospher*))) OR TS = ("carbon emission*" OR "sequestration of carbon" OR "sequester* carbon" OR "sequestration of CO2" OR "sequester* CO2" OR "carbon tax*" OR "CO2 abatement" OR "CO2 capture" OR "CO2 storage" OR "CO2 sequester*" OR "CO2 sequestration" OR "CO2 sink*" OR "anthropogenic carbon" OR "captur* of carbon dioxide" OR "captur* of CO2" OR "climat* variability" OR "climat* dynamic*" OR "chang* in climat*" OR "climat* proxies" OR "climat* proxy" OR "climat* sensitivity" OR "climat* shift*" OR "coupled ocean-climat*" OR "early climat*" OR "future climat*" OR "past climat*" OR "shift* climat*" OR "shift in climat*") OR TS = ("atmospheric carbon dioxide" OR "atmospheric CH4" OR "atmospheric CO2" OR "atmospheric methane" OR "atmospheric N2O" OR "atmospheric nitrous oxide" OR "carbon dioxide emission*" OR "carbon sink*" OR "CH4 emission*" OR "climat* policies" OR "climat* policy" OR "CO2 emission*" OR dendroclimatolog* OR ("emission* of carbon dioxide" NOT nanotube*) OR "emission* of CH4" OR "emission* of CO2" OR "emission* of methane" OR "emission* of N2O" OR "emission* of nitrous oxide" OR "historical climat*" OR IPCC OR "methane emission*" OR "N2O emission*" OR "nitrous oxide emission*") OR TS = ("climat* change*" OR "global warming" OR "greenhouse effect" OR "greenhouse gas*" OR "Kyoto Protocol" OR "warming climat*" OR "cap and trade" OR "carbon capture" OR "carbon footprint*"

OR "carbon neutral" OR "carbon offset" OR "carbon sequestration" OR "carbon storage" OR "carbon trad*" OR "changing climat*" OR "climat* warming")

Climate change mitigation (keyword terms taken from IPCC 2014)

TS = (("mitigation" AND "climate") OR "climate protection" OR "climate target" OR "climate goal" OR "climate stabili*ation" OR "decarboni*ation" OR ("emission*" NEAR/3 "reduction*") OR "climat* poli*" OR "climate action" OR "climate plan*" OR "climate agenda*" OR "climate legislation" OR "climate strateg*" OR "carbon tax*" OR "CO2 tax*" OR "GHG tax*" OR "carbon pric*" OR "CO2 pric*" OR "GHG pric*" OR "emission* tax" OR "emission* price" OR ("emission* trading" AND "climate") OR "emission* regulation" OR "low-carbon" OR ("biochar*" AND (("carbon" NEAR/3 "sequest*") OR ("carbon" NEAR/3 "storage") OR ("climate change" OR "global warm*"))) OR ("biochar*" AND (("carbon" NEAR/3 "sequest*") OR ("carbon" NEAR/3 "storage") OR ("climate change" OR "global warm*"))) OR ("ocean" NEAR/5 "iron" NEAR/5 "fertili*ation" NOT "natural" NOT "ice*") OR (("soil" NEAR/3 "carbon" NEAR/3 "sequest*") AND ("climate change" OR "global warm*")) OR (("afforestation" OR "reforestation") AND (("carbon" NEAR/3 "sequest*") OR ("carbon" NEAR/3 "storage"))) OR ("enhanced weathering" AND ("CO2" OR "carbon" OR "C(O2)") NOT "ice*" NOT "paleo*") OR ((("atmosph*" NEAR/5 "capture") OR ("air" NEAR/5 "capture")) AND ("CO2" OR "carbon" OR "C(O2)")) OR ("BECCS" NOT "bioactive equivalent combinatorial components" NOT "bandwidth-efficient-channel-coding-scheme" NOT "bronchial epithelial cell cultures") OR (("biomass" OR "bioenerg*") AND ("CCS" OR "Carbon capture and Storage" OR "Carbon dioxide capture and Storage" OR "CO2 capture and storage")))

IAMs

TS = ("integrated assessment" OR "integrated model*" OR "IAM" OR ("energy-economy-environment model*" AND "climate") OR "energy-economy-climate model*" OR ("economy-energy-environment model*" AND "climate") OR "economy-energy-climate model*" OR "economy-climate model*" OR "climate-economy model*")

Air pollution (top ten keyword terms from Xie et al., 2008 and Zhang et al., 2009, respectively)

TS = ("aerosol*" OR ("asthma" AND "aerosol*") OR ("asthma" and "particulate matter") OR "particulate matter" OR "PM 2.5" OR "PM2.5" OR ("air pollution" AND "health") OR ("air quality" AND "health") OR ("ozone" AND "aerosol*") OR "PM 10" OR "PM10" OR ("inhala*" AND "aerosol*") OR ("deposition" AND "aerosol*") OR "volatile organic compound*" OR ("VOC" AND "air") OR ("VOCs" AND "air") OR ("benzene" AND "air") OR ("toluene" AND "air") OR ("adsorption" AND "air") OR ("gas chromatography" AND "air") OR ("isoprene" AND "air"))

Energy security (keyword terms taken from excerpts of Cherp and Jewell, 2014)

TS = ("energy security" OR ("supply security" AND "energy") OR "security of energy suppl*" OR ("security of supply" AND "energy") OR ("availab*" AND "affordab*" AND "energy") OR ("access*" AND "energy sources") OR ("accepta*" AND "energy sources")

OR ("vulnerability" AND "energy system*") OR ("sovereignty" AND "energy") OR ("robustness" AND "energy") OR ("resilien*" AND "energy system*") OR ("flexib*" AND "energy supply") OR ("divers*" AND "energy system*"))

Biodiversity (keyword terms from Hassan et al., 2013)

TS = ("biodiversity conservation" OR "species-area relationship" OR "threatened species" OR "forest management" OR "habitat loss" OR "conservation planning" OR "invasive species" OR "nature conservation" OR "indicator species" OR "species richness" OR "plant diversity" OR "biodiversity" OR "protected areas" OR "marine biodiversity" OR "species diversity" OR "exotic species" OR "habitat fragmentation" OR "endangered species" OR "marine protected areas")

Water (keyword terms from Hassan et al. 2013)

TS = ("underground dams" OR "water and sanitation" OR "storage aquifers" OR "shared water" OR "floods monitoring" OR "optimal water use" OR "water productivity" OR "water grabbing" OR "water stressed countries" OR "water reuse" OR "water inventory" OR "water resources depletion" OR "water pollution" OR "water management" OR "water resources management" OR "water supply" OR "water scarcity" OR "water quality" OR "water reuse" OR "integrated water resources management" OR "water use efficiency" OR "watershed management" OR "water shortage" OR "soil and water conservation" OR "sanitation and water conservation" OR "water productivity" ("groundwater" AND ("sustainability" OR "sustainable development")) OR "water policy" OR "water pricing" OR "water balance" OR "water use" OR "water conservation" OR "water framework directive" OR "rural water supply" OR "water demand" OR "water resources development" OR "river basin management" OR "groundwater quality" OR "virtual water" OR "urban water" OR "water recycling" OR ("water resources" AND ("sustainability" OR "sustainable development")) OR "water security" OR "groundwater management" OR "water resource management" OR "groundwater recharge" OR "submarine groundwater discharge" OR "seawater intrusion" OR "groundwater flow" OR "groundwater contamination" OR "water stress" OR "surface water" OR "eutrophication" OR "rainwater harvesting" OR "drought stress" OR "drought" OR "drought tolerance" OR "desertification" OR "drought resistance" OR "water deficit" OR "palmer drought severity index" OR "drought avoidance" OR "flood risk" OR "flooding tolerance" OR "flood control" OR "flood defence" OR "flood damage" OR "river restoration" OR "flood management" OR "water logging" OR "flood forecasting" OR "flood simulation modelling" OR "infiltration based storm water management" OR "floodplain geomorphology" OR "urban floods" OR "flood hazard management" OR "flood warning" OR "floodplain restoration" OR "integrated watershed modelling" OR "integrated watershed management" OR "water quality index" OR "water footprint" OR "grey water" OR "green water footprint" OR "blue water footprint" OR "grey water footprint" OR "potable water" OR "wastewater management" OR "waste water treatment" OR "wastewater treatment plants" OR "wastewater treatment plant" OR "water reuse" OR "water treatment" OR "wastewater reuse" OR "municipal wastewater" OR "domestic wastewater" OR "stormwater management" OR "textile wastewater" OR "drinking water treatment" OR "sewage sludge" OR "water recycling" OR "wastewater treatment" OR (("estrogens" OR "estrogen" OR "estrogenic") AND ("water" or "wastewater" OR "river")) OR ("sulphonamides" AND ("water" OR "river") AND ("pollution" OR "pollutant" OR "pollutants" OR "contaminant" OR "contaminants" OR "contamination")) OR (("tributylphosphate" OR "octylphenol" OR "nonylphenol triazines" OR "organophosphorus" OR "acetanilides") AND ("'water" OR "river") AND ("pollution" OR "pollutant" OR "pollutants" OR "contaminant" OR "contaminants" OR "contamination")) OR ("pesticide" AND ("river" OR "water")) OR ("polycyclic aromatic hydrocarbons" AND ("water" OR "river")) OR (("brominated flame retardants" OR "pentabromoethylbenzene" OR "hexabromobenzene" OR "decabromodiphenylethane") AND ("river" OR "water")) OR (("atenolol" OR "propranolol" OR "carbamazepine" OR "clofibric acid") AND "fungus") OR (("estrogens" OR "estrogen" OR "estrogenic") AND "biosphere's reserve") OR (("pharmaceuticals" OR "pharmaceutical") AND ("river" OR "water")) OR ("wastewaters") OR (("water" OR "river") AND ("pollution" OR "pollutant" OR "pollutants" OR "contaminant" OR "contaminants" OR "contamination")))

References

Cherp, Aleh, and Jessica Jewell. 2014. 'The Concept of Energy Security: Beyond the Four As'. *Energy Policy* 75 (December): 415–21. https://doi.org/10.1016/j.enpol.2014.09.005.

Grieneisen, Michael L., and Minghua Zhang. 2011. 'The Current Status of Climate Change Research'. *Nature Climate Change* 1 (2): 72–73. https://doi.org/10.1038/nclimate1093.

Hassan, Saeed-Ul, Peter Haddawy, and Jia Zhu. 2013. 'A Bibliometric Study of the World's Research Activity in Sustainable Development and Its Sub-Areas Using Scientific Literature'. *Scientometrics* 99 (2): 549–79. https://doi.org/10.1007/s11192-013-1193-3.

IPCC. 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Minx, Jan C., William F. Lamb, Max W. Callaghan, Lutz Bornmann, and Sabine Fuss. 2017. 'Fast Growing Research on Negative Emissions'. *Environmental Research Letters* 12 (3): 035007. https://doi.org/10.1088/1748-9326/aa5ee5.

Xie, Shaodong, Jing Zhang, and Yuh-Shan Ho. 2008. 'Assessment of World Aerosol Research Trends by Bibliometric Analysis'. *Scientometrics* 77 (1): 113–30. https://doi.org/10.1007/s11192-007-1928-0.

Zhang, Gangfeng, Shaodong Xie, and Yuh-Shan Ho. 2009. 'A Bibliometric Analysis of World Volatile Organic Compounds Research Trends'. *Scientometrics* 83 (2): 477–92. https://doi.org/10.1007/s11192-009-0065-3.

8.2 Assessment Making – Exploration of the Whole Solution Space

This essay was written by Ottmar Edenhofer, Christoph von Stechow, Jan Minx, Martin Kowarsch as a contribution to the Wellington Accord, i.e. the agreements made at the 2nd IPCC WGIII AR5 Lead Author Meeting in Wellington, New Zealand, 19-23 March, 2012.

INTERGOVERNMENTAL PANEL ON climate change

Working Group III (WG III) – Mitigation of Climate Change

THE WELLINGTON ACCORD

AGREEMENTS MADE AT THE 2ND WG III LEAD AUTHOR MEETING

IN WELLINGTON, NEW ZEALAND

19-23 MARCH 2012

WMO UNEP

1. Assessment Making – Exploration of the Whole Solution Space

Ottmar Edenhofer, Christoph von Stechow, Jan Minx, Martin Kowarsch

A sound assessment of the "scientific, technical, and socio-economic literature" on mitigation is a crucial foundation for robust decision-making.[1] The importance of assessments for providing a better understanding of long-term climate change policy choices is rooted in three major challenges at the science-policy interface. First, there is no scientific resolution of value dissent underlying the climate change discourse. Second, facts and values cannot be separated neatly. Third, long-term policy choices are associated with fundamental uncertainties, which might not necessarily be reduced by science.

The neglect of addressing these challenges might lead to politization of science (and scientization of politics); jeopardize the credibility of science in policy and politics; and marginalize its potentially important role at the science-policy interface to meet societal needs. In order to be perceived as a "comprehensive, objective and balanced view of the subject matter" and as policy-relevant without being policy-prescriptive,[1] an assessment should hence fulfill all of the following requirements:

1) Reviewing comprehensively the relevant scientific, technical and socio-economic literature

The review of an assessment has a different character than a review article in a journal. While a review article usually summarizes the results of a particular scientific community on a specific topic, the review of an assessment should be comprehensive both with respect to topics covered and participation of different communities – including disparate views, methods, and diverging results for which there is significant scientific or technical support.

2) Describing consistent transformation pathways

By bringing together different communities, the ongoing communication between the experts during the process should help to identify (self-)consistent transformation pathways of response strategies to climate change. This is a crucial step towards the reduction of complexity around the subject matter.

3) Evaluating costs, risks and benefits of different pathways in a consistent way within and across Chapters and WGs

The exploration of alternative transformation pathways should allow for a critical reflection of means to achieve societal ends within the entire space of end-means-relationships: Each pathway should be characterized by its associated costs, risks and benefits. Synergies and trade-offs between different societal ends are thus highlighted across alternative pathways. Feeding these results back into the public sphere may result in adapted societal ends and related response strategies.

4) Specifying underlying value judgements and worldviews

In order to understand the reasons for divergence of results and possibly reconcile disparate views found in the relevant literature, the underlying assumptions related to particular value judgments, interests, beliefs or worldviews should be made explicit and related to each other in order to enable an informed discussion among policymakers and the public on possible transformation pathways.

5) Communicating quantitative and qualitative uncertainties

It is important to evaluate and communicate the respective degree of uncertainty of assessment findings in their quantitative and qualitative dimensions (see Uncertainty Guidance Note).[2] This

[1] IPCC 2011: "Procedures for the Preparation for the Review, Acceptance, Adoption, Approval and Publication of IPCC Reports. Appendix A to the Principles Governing IPCC Work", www.ipcc.ch/pdf/ipcc-principles/ipcc-principles-appendix-a.pdf.

[2] IPCC 2010: "Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties", http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

relates to problem framings, system boundaries, indicator choice, model structures, parameters, expert judgments and data etc.

6) Using neutral language along good scientific practice

Given the broad spectrum of users of assessment reports and of the assessed scientific, technical and socio-economic literature, scientific language should be used to prevent potential misconceptions that could undermine the impartiality and credibility of the author teams. Terms that are usually used in the policy arena should be used with care and in a policy-neutral way.

7) Making text, figures and tables accessible

Accessibility of the text, figures and tables are prerequisites for an assessment to be effectively used for guiding decisions. This includes the corresponding summary documents.

8.3 Commentary: A road map for global environmental assessments

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Abstract

Increasing demand for solution-oriented environmental assessments brings significant opportunities and challenges at the science–policy–society interface. Solution-oriented assessments should enable inclusive deliberative learning processes about policy alternatives and their practical consequences.

More than 140 global environmental assessments (GEAs) have been initiated over the past four decades[1]. There is ongoing demand for these diverse, large-scale, multi-stakeholder, typically intergovernmental processes that distil and synthesize knowledge to inform decision-making. GEAs are time consuming, demanding processes often facing institutional and political constraints. Nevertheless, compared with alternative science–policy–society interfaces, well designed GEAs have higher potential for legitimacy, governmental buy-in and generating credible syntheses across disciplines and approaches[2–4], particularly regarding 'wicked problems'[5]. GEAs have provoked and sometimes even shaped international negotiations[2]. For example, the assessments of the IPCC informed and catalysed support for the Paris Agreement[5], and the fifth Global Environment Outlook (GEO-5) assessment influenced the 2030 Development Agenda[6].

Desirable shift to solutions

Notwithstanding these successes, it is widely recognized that GEAs must evolve to improve their utility in integrating scientific and other expertise with policy processes[2,4,7]. Crucially, while many GEAs have effectively exposed environmental problems and drivers, the existing assessment of possible solutions has not yet reached its full potential. More clearly and extensively than ever before, decision-makers and scholars are demanding a deeper and more explicit focus on assessing different possible solutions in GEAs, including policies in particular (for example, regulatory measures or market-based instruments)[7–11]. Recent IPCC reform discussions help illustrate this (Figure 8.1).

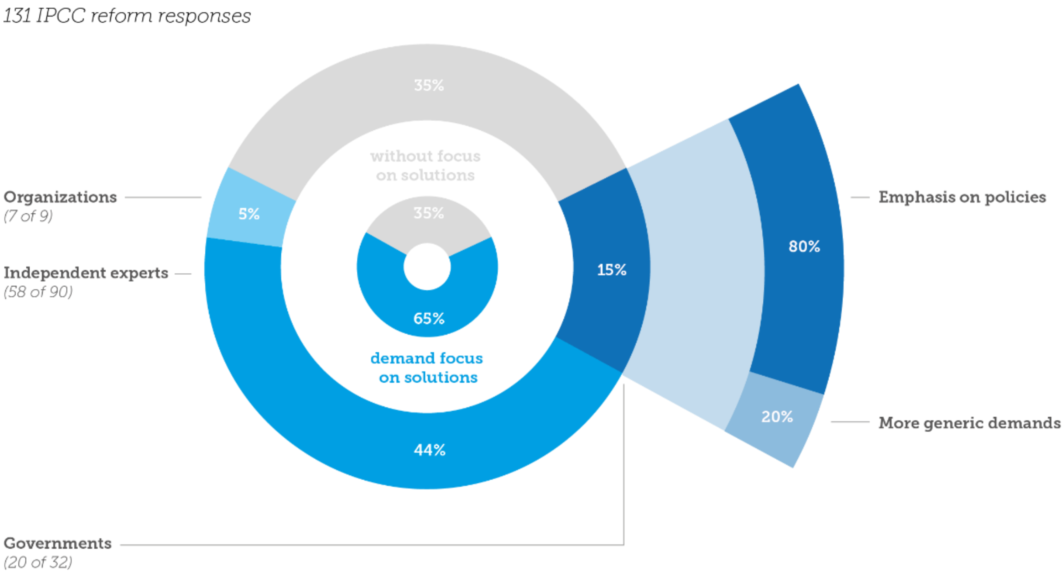

Figure 8.1 Various actor groups demand more solution-oriented IPCC assessments. Building on Jabbour and Flachsland[1], further analysis of 131 comments submitted to the IPCC by governments, organizations and independent experts in 2014 for the IPCC reform discussions reveals the extent of the demand (percentages are rounded) for more explicit assessment of solution options in future IPCC reports, and specifically of policies (demanded by 80% of the 20 solution-oriented government submissions). See Supplementary Section A.

Extensive policy assessment stands to reason given the recent developments in international environmental governance. The universal adoption of the Sustainable Development Goals (SDGs) and the Paris Agreement in 2015 were historic milestones in multilateralism and environmental governance. However, identifying and mobilizing the appropriate policies to pursue ambitious climate policy pathways or multiple SDGs remains a shortcoming and a priority. To this end, decision-makers are lacking sufficient knowledge about the direct effects, co-benefits and unintended adverse consequences of available policies across various dimensions, including multiple policy fields, governance levels, socioeconomic contexts, and time scales[9,12,13]. For example, policies restricting bioenergy deployment to protect food security, biodiversity and water availability increase the reliance on other contested technologies and the costs for climate change mitigation[13]. While uncertainty cannot be eliminated when assessing potential effects and interdependencies, their greater appreciation is crucial for managing these wicked problems. The GEA enterprise could become more relevant for advancing global sustainability by going beyond the (still necessary) assessment of environmental problems and priorities to explicitly engaging an integrated, contextualized evaluation of different environment-related policies and their complex effects. GEAs could, for instance, explore the implications of multilateral regimes or the global diffusion of domestic and regional policy lessons. Co-producing application-oriented, trans-disciplinary knowledge with an extended community of actors is crucial here[14–17].

However, to be successful, such solution-oriented GEAs must first address three profound challenges (see Supplementary Section C.a): integrating multiple policy dimensions, treating divergent normative viewpoints, and influencing policy. These challenges are intertwined, and are amplified by the evolving international environmental governance landscape. This evolving landscape has become characterized by the proliferation of consensual environmental goals without appropriate policies for their achievement, and by new constellations of actors (and power) increasingly including non-state actors at multiple scales[1]. Drawing from a larger interdisciplinary research project (Supplementary Section C.a), we provide a systematic overview of challenges and opportunities for contemporary solution-oriented GEAs in this evolving governance landscape. In particular, going beyond the largely fragmented literature on individual GEAs, this includes a unique synthesis — and substantive refinement — of some emerging GEA design approaches that may help address the challenges.

Three challenges of solution-orientation

The first challenge is assessing the various multi-dimensional effects of policies in a rigorous and highly integrated manner (without necessarily reconciling them). This has proven an onerous and sometimes overtaxing methodological undertaking thus far[4]. It is difficult enough to frame and scope suitable policy options in a complex solution space, as experienced in the Millennium Ecosystem Assessment (MA) and in GEO-5. The profound multidimensionality of the SDGs and the Paris Agreement goals create unprecedented complications for GEAs assessing options for achieving them.

Closely related is a second challenge: treating controversial normative viewpoints inherent to solution-oriented GEA processes that could undermine their legitimacy. Normative assumptions are inevitable in scientific research[12]. While explicitly incorporating them through inclusion of divergent worldviews, policy priorities, and so on of diverse stakeholders (Supplementary Section C.b) is an essential opportunity for GEAs, polarization can be triggered by divergent viewpoints — not only between author teams and other stakeholders, but also among authors themselves. For example, in the impressively inclusive International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), disagreements over the impacts of genetically modified organisms resulted in some private sector authors and members of the Bureau resigning. More recently, some governments resisted an ex-post evaluation of national policies by the IPCC[18]. The evolving governance landscape, involving a growing diversity and number of disputed policy priorities and stakeholders, has resulted in amplified tension in GEA processes.

The third challenge is facilitating meaningful GEA influence, mainly in terms of mutual learning[2,11,19]. Conventional thinking maintains that scientific consensus is a precondition to directly influencing policy decisions by governments. However, the complexity of current policy issues and the diversity of actors involved in the evolving governance landscape make a consensus on 'best' policy options virtually impossible. Fostering influence requires an improved understanding of the potential causal influence (that is, outcome and impacts in the policy arena) of solution-oriented GEAs in the evolving governance landscape, resulting from both their processes and outputs.

Enabling multi-dimensional policy assessment

The following interventions may be part of a strategic response to the first challenge of integrating multiple policy dimensions.

Given the proliferation of objectives for many contemporary GEAs as a result of the increasing multi-dimensionality[1], a deliberate focus on a limited number of collaboratively determined, specific policy questions of particular relevance to decision-makers (for example, distributional effects of policies) is a first step towards improving the feasibility of many GEAs, as already practiced by the UN Environment Emissions Gap reports and the IPCC special reports. Yet, the selected policy issues should be assessed in a way that also informs governance processes about key interdependencies and indirect effects across policy fields.

Following the example of the integrated scenario modeling community, the main organizational principle of solution-oriented GEAs could be to more resolutely assess coherent future policy pathways, including potential policies, their various effects and specific requirements. This would improve policy-relevance. Multiple (qualitative and quantitative) criteria and various (for example, agent-based) model types should be employed to assess different policy dimensions, disciplinary insights, and approaches in an integrated manner. This would also help better embed the social sciences and humanities in some GEAs, including the IPCC[11].

The aggregation of research results could be improved outside of assessment processes (as observed in the health and education sectors), through meta-analyses and systematic reviews, particularly in the peer-reviewed social-science literature. This should be organized along the multiple policy dimensions explained above, and would help GEAs deal with the rapidly growing body of literature (Figure 8.2). Equally important is addressing key research gaps outlined in previous solution-oriented GEAs, particularly regarding empirical ex post policy analysis to enable learning from past experiences for future policy design. A systematic ex post meta-study on existing policies for sustainability could be organized, for instance, analogous to Elinor Ostrom's comparative analysis[20] of local common-pool resource management. This would help identify empirical factors conducive to successful environmental management in the context of multiple societal goals rather than continuing theoretical disputes in the social sciences.

Accommodating divergent normative viewpoints. To address the second challenge, GEAs must avoid polarization (of issues and stakeholders) and technocratic policy prescriptions while still constructively addressing controversial policy issues. The Intergovernmental Platform for Biodiversity and Ecosystem Services, for example, is deliberately positioned to become a learning opportunity for the meaningful inclusion of multiple worldviews, knowledge and value systems through diverse stakeholders (Supplementary Sections C.b and C.c).

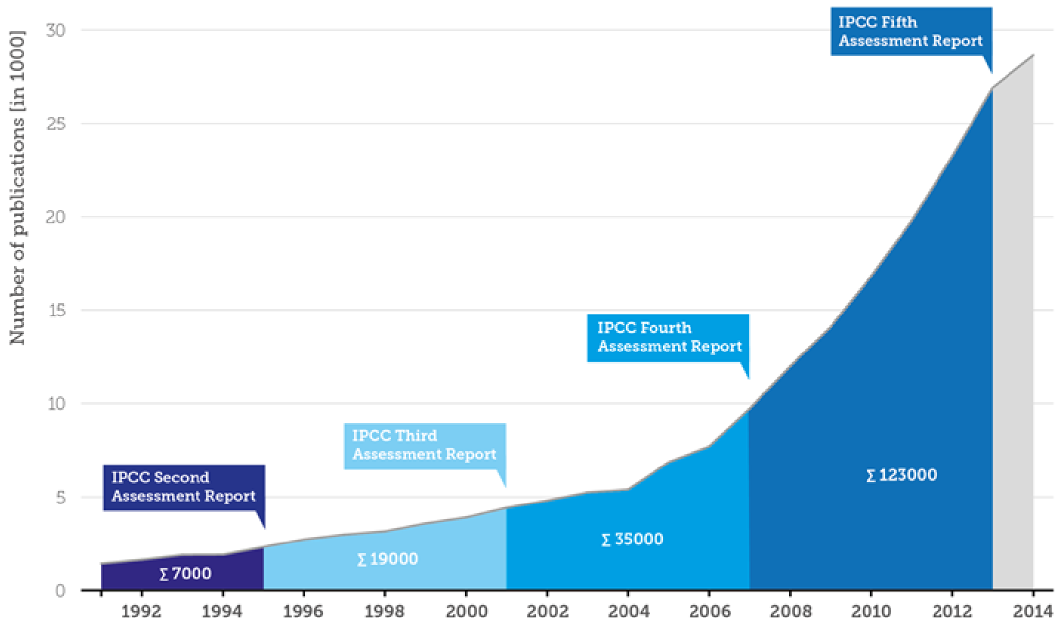

Figure 8.2 Rapid growth of annual publications on 'climate change'. We considered publications between 1990 and 2014 (212,000 in total) as listed in Web of Science, following Grieneisen and Zhang[24]. Numbers are rounded. In 2014 alone, more papers (29,000) were published than in the entire period between Assessment Report 1 (AR1) and Assessment Report 3 (AR3) by the IPCC (26,000). See Supplementary Section B.

More specifically, solution-oriented GEAs, through inclusive and transparent processes, may collaboratively select, scientifically explore and critically assess alternative policy pathways including their diverse practical implications[12], taking into account a diversity of knowledge systems and perspectives[17]. No consensus on specific problem framings or solutions is needed, but consistency in approaches is required to facilitate comparison[12]. Only a few past GEAs have seriously explored alternative policy pathways, including the recent IPCC Working Group III assessment[12] and, to a lesser degree, the MA. The pathways explored should represent alternative policy narratives and objectives. Through the exploration of alternative pathways, GEAs can also reveal tensions between developing and developed countries and address them more explicitly[9,21]. GEAs should identify and communicate the underlying reasons for disagreement when evaluating policy pathways. These approaches can significantly increase the legitimacy of GEAs and enable iterative, deliberative learning processes[4,5,22] among different stakeholders about policy alternatives while making it harder for interest groups to steer GEAs in a particular direction.

Acknowledging the multiplicity of approaches through which stakeholders can be engaged within GEA processes, a simple but effective measure for many solution-oriented GEAs to improve these methods would be to better align them with their objectives (Supplementary Section C.c.) and available resources. This could be done, for example, by strengthening and formalizing the protocols and institutions guiding stakeholder selection and methods of engagement (for example, the Multi-Stakeholder Bureau supporting the IAASTD assessment) to ensure clear objectives, fair representation, cohesive engagement approaches, and use of outputs in GEAs[14].

Interacting with new target groups

Addressing the third challenge requires better recognizing and fostering of the broad range of possible GEA influences on policy discourses. These include often-concealed forms of influence that solution-oriented GEAs exert through co-production of knowledge and interactive deliberations with various stakeholders[19]. Examples include: agenda-setting, shaping networks in international negotiations, the diffusion of programmatic policy ideas (for example, carbon pricing), and bidirectional learning between scientists and policy-makers. Thus, a potential, desirable and often underestimated outcome of solution-oriented GEAs in the evolving governance landscape is the enrichment of policy discourses among various state and non-state decision-makers through open multi-stakeholder learning processes around policy alternatives. Different measures may help realize this outcome.

Solution-oriented GEAs should recognize new and diverse target groups[21]. International environmental governance processes typically include, for instance, coalitions of local governments (for example, C40 Cities Climate Leadership Group) and business associations concerned with sustainability (for example, World Business Council for Sustainable Development). Depending on available resources, GEAs could organize separate dialogue forums with each group before, during and after GEA processes.

By encouraging direct interactions between these groups, GEA processes can enhance mutual learning, enable researchers to identify windows of opportunity, re-animate environmental debates, and facilitate discussions about relevant socioeconomic and political conditions[19]. Inspiring approaches to structure such encounters include: co-producing different summaries with different target audiences (for example, GEO-5)[14]; positioning special experienced translators between scientific expertise and policy (for example, UN Chief Scientists); and organizing regular face-to-face dialogues between scientists and policymakers, such as the successful Structured Expert Dialogue on international climate policy involving IPCC experts (2014–2015).

Reforms embedded in a learning process

To conclude, future assessments should, in contrast to current populist ideas, facilitate inclusive, interactive and deliberative learning processes about actual policy alternatives and their different implications and interdependencies. Then, GEAs can more meaningfully contribute to policy discourses, which are a major factor contributing to policy change[19] — particularly when emphasizing solution options. In this sense, GEAs can take advantage of the current solution orientation in environmental governance and may help decision-makers make more robust policy decisions given multiple objectives, complexity and uncertainty.

Given the vast diversity of GEAs and their important distinctions from traditional assessment approaches, our recommendations are not blueprints and require contextualization. These promising GEA reform options must be (further) tested in adaptive learning processes where feedback is openly obtained and the GEA strategies are appropriately adjusted, for instance in the upcoming sixth IPCC assessment cycle. To facilitate learning from experimental phases of GEA design, scientifically robust investigations into GEA impacts and their enabling conditions should become routine after every GEA, incorporating more nuanced and comparable impact metrics than standard user surveys. This would provide the responsible scientific and policy communities, including assessment practitioners, various stakeholders and governments who are mandating assessment processes, with a transparent basis for judging, comparing and adjusting GEA methodologies and processes. This will help GEAs to effectively contribute to better governance of pressing global threats[23].

Acknowledgments:

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Additional Information:

Supplementary Information is available in the online version of the paper and below.

References

1. Jabbour, J. & Flachsland, C. *Environ. Sci. Policy* **77**, 193–202 (2017).
2. Mitchell, R. B., Clark, W. C., Cash, D. W. & Dickson, N. M. (eds) *Global Environmental Assessments: Information and Influence* (MIT Press, 2006).
3. Kowarsch, M. *Nat. Clim. Change* **6,** 15–17 (2016).
4. Norgaard, R. B. *Conserv. Biol.* **22,** 862–869 (2008).
5. Kowarsch, M. *et al. Palgrave Comm.* **2,** 16092 (2016).
6. Dodds, F., Laguna-Celis, J. & *Thompson, L. From Rio+20 to a New Development Agenda: Building a bridge to a sustainable future* (Routledge, 2014).
7. Perrings, C., Duraiappah, A., Larigauderie, A. & Mooney, H. *Science* **331,** 1139–1140 (2011).
8. *The Future of Sustainable Development: Rethinking Sustainable Development After Rio+20 and Implications for UNEP* (IISD, 2013).
9. Carraro, C. *et al. Science* **350,** 34–35 (2015).
10. Lee, H. *Science* **350,** 1007 (2015).
11. Victor, D. G. *Nature* **520,** 27–29 (2015).
12. Edenhofer, O. & Kowarsch, M. *Environ. Sci. Policy* **51,** 56–64 (2015).
13. von Stechow, C. *et al. Environ. Res. Lett.* **11,** 034022 (2016).
14. Garard, J. & Kowarsch, M. *Environ. Sci. Policy* **77**, 253–243.
15. Funtowicz, S. O. & Ravetz, J. R. *Futures* **25,** 739–755 (1993).
16. Nowotny, H., Scott, P. & Gibbons, M. *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty* (Polity Press, 2001).
17. Fabricius, C., Scholes, R. & Cundill, G. in *Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment* (eds Reid, W. V., Wilbanks, T., Capistrano, D. & Berkes, F.) 165–182 (World Resources Institute, 2006).
18. Edenhofer, O. & Minx, J. *Science* **345,** 37–38 (2014).
19. Riousset, P., Flachsland, C. & Kowarsch, M. *Environ. Sci. Policy* **77,** 260–267 (2017).
20. Ostrom, E. *Governing the Commons: the Evolution of Institutions for Collective Action* (Cambridge Univ. Press, 1990).
21. Petersen, A., Blackstock, J. & Morisetti, N. *Nat. Clim. Change* **5,** 909–911 (2015).
22. Dietz, T. *Proc. Natl Acad. Sci. USA* **110,** 14081–14087 (2013).
23. Haas, P. M. *Epistemic Communities, Constructivism and International Environmental Politics* (Routledge, 2015).

Supplementary Information

This supplementary file provides the methods and material underlying Figure 8.1 (including Figure S-8.1, Tables S-8.1-S-8.3) and Figure 8.2 (including Table S-8.4) as well as some more background on the three challenges and stakeholder engagement.

A. Method underlying Figure 8.1

According to the principles governing the work of the Intergovernmental Panel on Climate Change (IPCC), these as well as the procedures shall be revised periodically to constantly improve the IPCC's operations, procedures and products. Upon conclusion of the fifth assessment cycle, during its 37th session in Butami, the IPCC plenary initiated a task group on the future of the IPCC, calling for input from governments, observer organizations and scientists involved in the IPCC process.[38] This process resulted in the comments that underlie Figure 8.1 and provide information about the 'demand side' of global environmental assessments (GEAs). While the authors acknowledge that the IPCC context cannot be generalized to other GEAs, these results are presented as illustrative for current thinking about GEAs.

In total, 137 official comments were submitted from Governments[39], Authors, Contributing Authors and Review Editors[40], International and other Organizations[41], 32 of which were submitted by governments, 90 by independent experts, and 9 by organizations. The nature of the comments illustrates the explicit demand across various actor groups for future IPCC reports to more explicitly assess solutions in general, and to focus on policy analysis in particular (see Figure S-8.1 for a comprehensive overview). This result was obtained by analyzing the comments with respect to their orientation towards 'solutions' (column "Solution-oriented comment" in Tables S-8.1, S-8.2 and S-8.3) and with respect to their focus on policy analysis (column "Emphasis on policies" in Tables S-8.1, S-8.2 and S-8.3).

In particular, comments were judged to be solution-oriented if they included key words such as:

- Solution(s)
- Technology/technologies, practice(s)
- Measure(s)
- Technical potential
- Engineering
- Mitigation/adaptation potential/option(s)/effort
- Policy-relevant, demanded by policymakers, addressed to policymakers
- Governments define topics
- Economic analysis, sectors
- Decision(s)
- Development alternatives

[38] https://www.ipcc.ch/meetings/session37/p37_decision_future.pdf
[39] https://ipcc.ch/apps/eventmanager/documents/11/280220141142-inf1_future_of_ipcc_govt_comments.pdf
[40] https://ipcc.ch/apps/eventmanager/documents/17/100920140349-INF.1-%20Future%20Work%20of%20IPCC-Compilation%20submissions.pdf. This document also includes six comments submitted by the Technical Support Units (TSUs) and the IPCC Secretariat which were not taken into account in our analysis due to the mainly procedural nature of the comments.
[41] https://ipcc.ch/apps/eventmanager/documents/17/090920140449-INF.1,%20Add.1%20-%20Future%20Work%20of%20IPCC%20-%20Compilation%20of%20submissions.pdf

- Growth potential
- Achieving/transition to SDGs, building resilience
- Synergy/synergies, win/win
- Co-benefits
- SREX

Similarly, comments were judged to focus on policies if they included key words such as:

- Policy
- Policy instrument(s), analysis, tool(s), design, alternative(s)
- Incentives
- Response, respond to climate change
- Response measure, strategy
- Strategy
- Priorities
- Governance
- Action, actionable knowledge
- Address(ing) (options, salient questions, climate change mitigation and adaptation etc.)
- Recommending/recommendation(s)
- Implementing/implementation
- Experience(s)
- Approach(es)
- What works…? What do we do…?
- Good/best practice
- Climate finance/financing
- Financial instrument(s)
- Investment

While these keywords played a central role in analyzing the comments, this analysis (building on, but refining and amending the analysis presented by Jabbour and Flachsland, 2017) also took into account the specific contexts in which the keywords occur which enabled a more appropriate and differentiated interpretation of the comments.

Please note that based on personal conversations and the high-level involvement of some of the co-authors of this paper in the recent IPCC assessment process, we know that IPCC reform comments suggesting “more focused” IPCC reports (e.g. similar to the “SREX”), for instance, typically have in mind more solution-orientation and higher relevance of IPCC reports for decision-making processes.

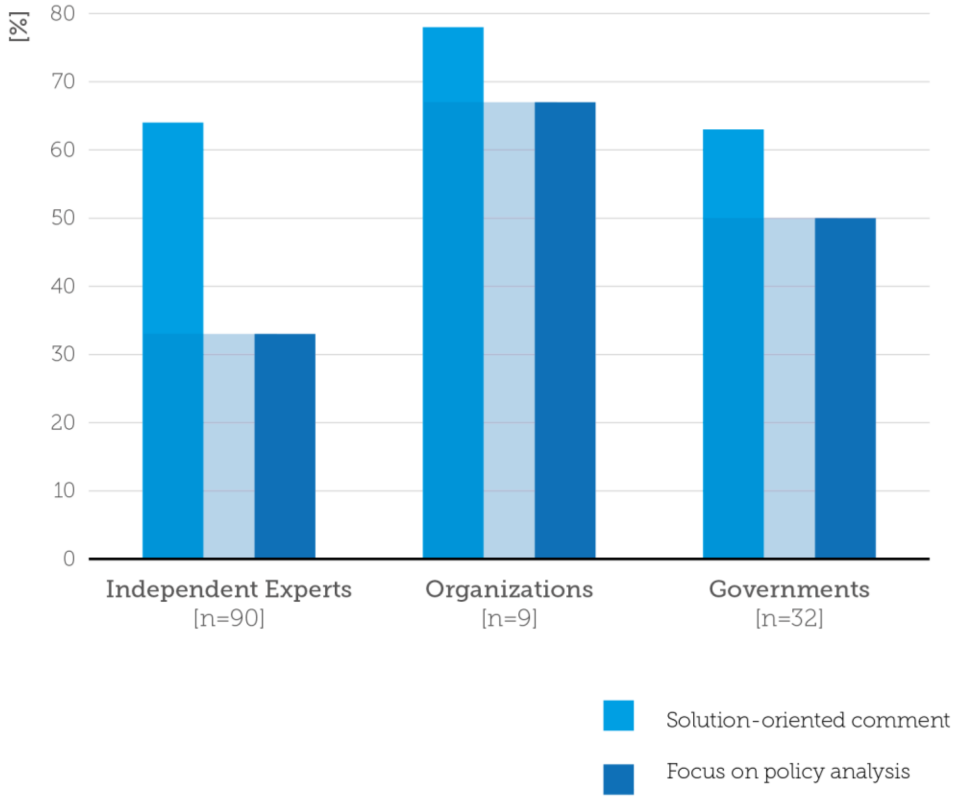

Figure S-8.1. The share of comments of governments, independent experts and organizations that submitted solution-oriented comments (light blue) and with an emphasis on policies (blue). This figure summarizes all results while Figure 8.1 in the main text focuses particularly on the comments by governments.

Table S-8.1 Independent Experts

Independent experts	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
Independent expert	"...A distinction between the problem and the solutions ...and the need to address options, experiences, syn**ergies, win-win and co-benefits and tradeoffs between adaptation and mitigation with the goal to enhance sustainable development** for all and in order to properly assess questions of justice."	1	1
Independent expert	"...offer an assessment of scienctific literature on the reasons for lack of success in realizing the goals and implementing to previous decisions adopted...**assess the scientific policy alternatives** to multilateral treat-based climate diplomacy...address promising unilateral and multilateral pathways towards a transition to SDG"	1	1
Independent expert	"**A clear shift in focus to solutions.** The IPCC has been very successful in defining the threat of climate change and raising awareness. Governments, business and the public are now looking for information on how they might respond" – what works and what doesn't work. This can be done in a manner that is not policy prescriptive"	1	1
Independent expert	"**Direction and strategy for mitigation and adaptation measures ...solutions for potential climate changes**. Link the activities of IPCC to MDGs and improvement of energy access through investment for energy efficiency and renewables"	1	1
Independent expert	"Greater focus on climate finance needs, flows, policy/financial instruments and their effectiveness"	1	1
Independent expert	"A special report which central focus is assessing these links as well as the multiple strands of existing literature on climate resilient pathways linking adaptation and mitigation will be of great value for any UNFCCC decisions made in 2015."	1	0
Independent expert	"...publish an annual (or biennial) bulletin that incorporates: updated factors, new methods and examples of good practices....examples of application of good practices can be prepared according to difficulties experienced by countries in implementing..."	1	1
Independent expert	"the IPCC should call for more research on [energy] development alternatives for [countries in transition] and then summarise the achieved results in AR6."	1	0
Independent expert	"...structure reports or emphasis on particular types of content to persuade the intransigent economic groups"	1	0
Independent expert	"...taking a more proactive role in developing and implementing climate change policies/laws, in particular, policies/laws related to mitigation opportunities and emissions constrains. As a basis for such policies and to better understanding the GHG emissions and removals"	1	1

Independent experts	Comments (relevant excerpts)	Solution-oriented comment	Emphasis on polices
Independent expert	"Midterm report …on policy and economic aspects before integrated into the AR should be considered"	1	1
Independent expert	"[Future] IPCC Assessment Reports [should] represent in a condensed form the available knowledge and reflect the scientific consensus on the climate change in future and **the availability of solutions**."	1	0
Independent expert	"there is a need for a transition of sorts… surely the questions change to "what do we do about it?" There is now an imperative to recognize that climate change is with us and we must plan for it in every way possible. Part of this relates to what does develop under GFCS and climate services"	1	1
Independent expert	"...regional reports **to enable better localization of climate change** problems **and solutions in concrete locations**."	1	0
Independent expert	"The IPCC …requires new policy oriented yet scientific leader….Awareness of what is and what is not societally relevant is a matter of framing issues in specific ways.	1	1
Independent expert	"Shorter, more focused reports that answer specific emerging **questions ….arising from the policy process**"	1	1
Independent expert	"a hiatus from the comprehensive reports should be taken for a number of years. The focus for a few years should be placed on …special reports that are carefully targeted to address specific, salient questions that are of high scientific, policy and social importance."	1	1
Independent expert	"Special reports where governments define topics…"	1	0
Independent expert	"Shorter reports on select topics as demanded by policy makers"	1	0
Independent expert	"specific guidance for those countries to be able to go from Tier 1 guidance to Tiers 2 or 3 including suggested approaches and potential sources and costs of acquiring the necessary data and synthesis."	1	1
Independent expert	"evolution towards assessments that focus more on what has changed in our understanding…need to strengthen participation from the private sector….evolution towards clearly-defined quantitative metrics [for] mitigation cost and investment.."	1	1
Independent expert	"Policy briefings and information with practical information"	1	1
Independent expert	"as Ars have matured, there has naturally been an evolution towards clearly-defined quantitative metrics (….) and estimates of their uncertainty…their role in informing risk management could help the next assessment….[need for] **greater flexibility in assessing economics literature on options and policies.**."	1	1

Independent experts	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
Independent expert	"…[need for a an improved] systematic co-exploration where the science of regional responses are evaluated through the lens of WG2/3 concerns…"	1	0
Independent expert	"…more focused …limited reports focused on progress achieved since previous report"	1	0
Independent expert	"Topical reports, answering concrete policy relevant questions"	1	0
Independent expert	"product should be aimed at actionable knowledge and directly address critical issues…more user-relevant scales…emphasis should be given to synthesizing the findings and mapping them to applicable knowledge"	1	1
Independent expert	"Relatively frequent special reports indicating major changes in understanding or developing them (e.g., SREX) and occasional executive and technical summaries of the state of the science"	1	0
Independent expert	"I suggest the development of new information **products oriented to society, and focused on simple facts and actions**."	1	1
Independent expert	"…disconnect between assessment of the costs of climate change, evaluated in WG II (though usually not in economic terms) and assessment of the costs of mitigation, evaluated in WG III. This undermines the cost-benefit analyses that are sorely needed for the world to make rational decisions, as much as possible, on how to respond to climate change."	1	1
Independent expert	"Examples of application good practices can be prepared according to difficulties experienced by countries in implementing them or where areas of further clarification are identified"	1	1
Independent expert	"issue-specific reports … particularly targeted toward informing sector-specific adaptation/mitigation efforts authored by smaller task forces"	1	0
Independent expert	"advocate a series of topic reports, similar to SREX…"	1	0
Independent expert	"…the main conclusions from old assessment reports are mainly the same…focus on important new insight we need new ways to avoid [a situation' where every sentence has to be approved…	1	0
Independent expert	"…unified quantification approach for emissions and sequestration… management approaches"	1	0
Independent expert	"…identification of the regions that will be most directly affected and recommendations about remediation (engineering approaches).."	1	0
Independent expert	"…IPCC spend too much time discussing model projections… economic analysis of AR5 was perhaps the most important new information that was provided.."	1	0

Independent experts	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
Independent expert	"focused regional level reports on mitigation and adaptation options, strategies and responses at 5-10 year intervals"	1	1
Independent expert	"focus on assessment and evaluation of adaptation plans and actions implemented. Specific plans and actions are more likely to have been reported in government documents and grey literature…."	1	1
Independent expert	"these major reports have outlived their value. Future products ...should therefore be targeted on specific areas in climate science adaptation, mitigation and –perhaps most importantly - specific economic sectors and aspects of the human economy"	1	0
Independent expert	"[future reports] should be focus how to go about building resilience at all scales"	1	0
Independent expert	"Sector-based products may well be more useful than more 'business as usual' reports"	1	0
Independent expert	"…address promising unilateral and multilateral pathways towards a transition to sustainable development goals addressing the need to drastically reduce GHG emissions by a progressive decarbonization of the energy, transportation, agriculture, production and housing sectors and the potential peace dividend of such a policy strategy that aims at resource efficiency and a replacement of fossil energy sources with renewables"	1	1
Independent expert	"Focused sectoral reports on learnings from adaptation and mitigation actions for the advancement of the global community knowledge."	1	1
Independent expert	"produce summary reports spot on the LDCs enclosed recommendations and advices to decision maker could be more valuable."	1	1
Independent expert	"one WG focusing on the physical science aspects and impacts of climate change from global to regional, and a second WG focusing on the solution space, including adaptation and mitigation."	1	0
Independent expert	"…highlighting specific challenges and opportunities related to climate system variability and changes on which place-based actions are possible."	1	1
Independent expert	"Increased attention is therefore suggested on strengthening the assessment of what emissions inventories mean in terms of impacts… A further consideration for the appropriate structure and modus operandi for the production of the IPCC products, focuses on the important role of involving experts from the energy sector. These experts are critical in a number of areas, including: in addressing technologies for mitigation; assessing practices for adaptation; methodologies for emissions estimation."	1	0

Independent experts	**Comments (*relevant excerpts*)**	**Solution-oriented comment**	**Emphasis on polices**
Independent expert	"deliver [assessments that] provide the scientific evidence for synergistically addressing: climate change adaptation and mitigation, food security, combating land degradation and desertification, while maintaining ecosystems services, including biodiversity."	1	1
Independent expert	"[Future IPCC] Report must be further developed and strengthened to help identify current priorities and adaptation needs in specific countries and societies, especially in highly vulnerable regions."	1	0
Independent expert	"Develop... a repository of successful (and not-successful) policy experiences and options, technologies, financing mechanisms, and educational/awareness raising actions…"	1	1
Independent expert	"The IPCC needs to commit to the eligibility of assessing regional policies and emissions in the reports. Climate change and climate policies cannot be sensibly assessed without regional specificity"	1	1
Independent expert	I feel we have become so concerned about the scientific validity of our reports that, while perhaps technically accurate, our reports have very little capacity to be digested and discussed among non-scientists (including policymakers), much less motivate social responses.	1	0
Independent expert	"More focused reports on questions of immediate interest to policy makers. SREX provides an example…geoengineering as an abatement strategy, ….food security, and the role of shale gas in carbon mitigation….evaluating leakage issues.	1	0
Independent expert	"…more guidance to capture their carbon footprint…National GHG inventories, increased use of multimedia	1	0
Independent expert	"Ranking for cost effectiveness of mitigation options in each sector."	1	0
Independent expert	"**Reports focused on Adaptation and Mitigation should receive stronger focus**. Consider the 2020 climate change agreement for planning the report publication."	1	0
Independent expert	"Updated analysis of renewable energy options highlighting both technology needs and economic investments needed to transform our current energy systems to a low carbon state"	1	1
Subtotals		**58**	**30**

Table S-8.2 Organizations

Organization	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
International Organization (Climate Action Network)	"...**increase understanding of alternative models of economic growth** that are decoupled from greenhouse gas emissions, the IPCC should call for **more research on development alternatives** for these countries and then summarise the achieved results in AR6...include a short description and analysis of this situation on governance..."	1	1
Observer (State of Palestine - Environment Quality Authority)	"... crosscutting issues require special attention for example, climate financing and response measures.."	1	1
International Organization (START Secretariat)	"... [new focus] on low carbon growth potential and related incentives-tradeoffs might foster better opportunities for concerted actions by IPCC member nations. Likewise special reports that deal with urban-rural linkages seem most timely."	1	1
International Organization OECD	Understanding of climate science and climate impacts has evolved considerably since the IPCC's First A). Focusing future reports on areas that are currently less certain could allow for the structure of future ARs to be streamlined, e.g., by merging assessments on the physical science basis and assessing the risks and impacts of climate change (i.e., working groups 1 and 2). The OECD considers "special reports" useful, and supports their continued preparation. These are particularly useful as they can be prepared on a shorter timescale than the assessment reports. Possible topics for upcoming special reports could include the economic impact of inaction, impact of climate change on achieving sustainable development goal(s), or SRs on the expected climate and economic impacts on a specific region.	1	0
International Organization (UNCCD)	"UNCCD recommends that further attention be given to [adaptation measures] in the future IPCC work. Constraints on implementation of adaptation are coming from uncertainty in the impacts, limited resources to develop effective policies, lack of guidance on principles and priorities, limited coordination of governance, different perceptions of risks, competing values, absence of adaptation leaders and advocates and limited tools to monitor adaptation effectiveness. Addressing adaptation throughout the world will ultimately require a diverse set of local-level, **context-specific solutions and the blending of traditional and modern knowledge and technologies**. **We recommend that these issues be given due attention in future IPCC reports**..."	1	1

Organization	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
International Organization (UNEP)	"IPCC Assessment Report must be further developed and strengthened to help identify current priorities and adaptation needs in specific countries and societies, especially in highly vulnerable regions. A shorter cycle report...[with a] focus on emerging science, especially when there are new trends or developments, **and solutions** and reflect the issues/developments relevant to the three IPCC working groups. The feature focus of the report might as well be chosen based on the demands from UNFCCC parties/IPCC member states."	1	1
University of Nijmegen	"Develop – in cooperation with other UN agencies - a repository of successful (and not-successful) **policy experiences and options, technologies, financing mechanisms**, and educational/awareness raising actions/campaigns."….Each of these groups consists of subject experts, **climate policy experts**, governmental representatives... Focus on special areas of societal and policy relevance, new insights and controversial issues."	1	1
Subtotals		**7**	**6**

Table S-8.3 Governments

Country	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
Argentina	"important to move forward to cross-cutting approaches among different Working Groups...Group III evaluates adaptation strategies and mitigation, enabling, at the same time, analysis of synergies"	1	1
Austria	"A high priority for the IPCC to produce fact track products to respond to urgent needs at the policy level"; "responses to the climate change risks, including adaptation and mitigation, should be addressed by the second Working Group."	1	1
Belgium	"Providing information that is useful for the policy processes and underpinning policy development without being policy prescriptive; ...the challenge of how to be more policy-relevant without being policy prescriptive;" ...The IPCC might have to consider a modification in the assessment cycle, the type of products useful for policymakers, ...A re-organization of the 3 current working groups (keeping the TFI as it is) in 2 new groups: Group 1 - Mechanisms: climate and impacts; physical climate change impacts on ecosystems and human activities - **Group 2 - Solutions: Mitigation, adaptation and vulnerability:** Scenarios, role of socio-economic drivers in shaping emissions, mitigation potential, adaptation potential, and vulnerability; Technical potential; Costs Transition, links with sustainable development"	1	1
Brazil	"For the next decade, emphasis should be placed on …the needs arising from the implementation of the post-2020 agreement under the Convention. Focus should be placed on "fast track" products, such as …the necessary **inputs and tools for** … further **developing and implementing their policies and actions**."	1	1
Canada	"provide information that would support a future UNFCCC review of long-term global climate, mitigation goals. Canada encourages the Task Group and/or Secretariat to consult with the UNFCCC early in these deliberations…. [concerns regarding lack of policy utility] "Canada is open to exploring suggestions for other WG structures …such as a **structure oriented towards articulating the "challenge" and "solutions"** to climate change. Canada sees merit in this type of structure.	1	0

Country	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
EU	"physical science basis and the assessment of associated impacts, risks and vulnerabilities' while the second part should **focus on the 'response measures: adaptation and mitigation'.** Such an approach will allow for a more coherent treatment of cross-cutting issues, m**ark a clearer distinction between 'diagnostics' and 'solutions/proposed measures' and also make it easier for policy makers to extract relevant information.** It will also cover adaptation and mitigation in an integrated manner –which is highly pertinent for policy making- and also facilitate the final synthesis of the assessment report.	1	1
Finland	"Although many key decisions in international climate policy are still to come, there is a lot of material for policy analysis during a 6-7 year assessment cycle. "	1	1
Germany	"IPCC assessment reports (ARs) and Special Reports (SRs) should become more concise with an **increased focus on policy relevant topics**. This would increase their usefulness for policy makers and reduce the workload for authors… enhancing the flexibility and the **responsiveness of the IPCC to policy needs**, in particular of the Parties to the UNFCCC."	1	1
Japan	"As overall tasks for the future, … reports focusing on practical and applicable mitigation and adaptation measures in each region or sector, taking the post-2020 international regime on climate change into consideration. Those reports should contribute especially to increasing knowledge of mitigation and adaptation measures applicable to developing countries. ...normative studies as well as empirical knowledge become important in relation to issues such as an assessment of geo-engineering. **…increased emphasis on response strategies.**"	1	1
Latvia	"More information compilations addressed to the policymakers"	1	0
Mali	"Strengthen adaptation and vulnerability measures, especially for developing countries..."	1	0
Nether-lands	"**Informing the international community about the scale of the problem and the availability of solutions and providing legitimacy for national climate policies**… recognizes and supports a growing demand for information that can support local decisions." ...**Both adaptation and mitigation solutions could be included**, which require different practical hand-on protocols, assessment methods and decision tools (e.g., **risk profiles; economic appraisal tools; finance tools; methodology for producing mitigation road maps**; portfolio management for adaptation and mitigation)."	1	1
Norway	"IPCC could exploit pre-policy analyses of audiences and user groups, as part of the scoping."	1	1

Country	Comments (*relevant excerpts*)	Solution-oriented comment	Emphasis on polices
Saudi Arabia, Kingdom of	"some crosscutting issues require special attention for example, climate financing, response measures, emerging issues	1	1
South Africa	"The IPCC should focus far more strongly on encouraging advancing the technologies and tools of impacts and adaptation assessment	1	0
Spain	"...consider grouping IPCC work in two main WGs: (i) physical science of climate change....and (ii) **responses/proposal to climate change challenge** in the field of adaptation and mitigation. The latter group – responses- can address some sectors with a clear win-win approach (agriculture, forestry, soils, health…), and others with a more independent way between adaptation and mitigation. This **WG on solutions can be structured according to a sectoral approach**."	1	1
Switzerland	"We propose to improve the IPCC products and to expand the activities [of the IPCC] …Assistance in the **elaboration of Policy Tools such as**: Manual for Adaptation Planning; Manual for Technology Assessment; **Optimization of Policy Design; Optimization of Environmental Synergies**"	1	1
Thailand	**"Increased [focus] on the solution side, best practice and** examples of current problems and adaptation in each region should be included… reports should be developed to identify … adaptation in specific countries, in particular in high vulnerability regions. IPCC should provide the pilot projects that illustrate m**anagement [tools] and technologies**"	1	1
UK	"..the need for policy makers to have answers to policy relevant questions, which don't readily map to specific WG reports.	1	1
USA	"**Re-work the substance on adaptation and mitigation options currently contained in WG2 and WG3 into a report on the "solution space" (i.e., mitigation and adaptation) for climate change**. Such a report could still be on a 5-7 year cycle, but more staggered from the WG1 report to ensure the scientific communities have sufficient time to digest and publish the results from the WG1 literature."	1	1
Subtotals		**20**	**16**

B. Method underlying Figure 8.2

Scientometric / bibliometric studies of the climate change literature remain relatively scarce. The study by Grieneisen and Zhang (2011) is a first attempt to provide a comprehensive overview of the field of climate change research based on a systematic and sophisticated search query. The study showed an exponential increase in publications between 1991 and 2009.

We apply the same search query to extend the analysis to understand whether this trend has continued in subsequent years. A complete description of the research methodology is included in the paper by Grieneisen and Zhang (2011) and does not need to be replicated here. We are able to closely reproduce the results for the period 1991-2009. We find that the exponential growth in the climate change literature has continued between 2009 and 2014. In fact, 2014 provides first evidence that this trend may start to break in the near future and continue at decreasing rates. However, no conclusions can be drawn from a single data point on this matter and only time can tell whether this really marks a change in the growth pattern.

The Intergovernmental Panel on Climate Change (IPCC) assesses the state of climate change research every five to seven years. These assessments ought to be undertaken on a comprehensive, objective, open and transparent basis. We roughly approximate the magnitude of the new literature that has accumulated over an assessment cycle by assigning all studies that have appeared before the year of publication of the synthesis report summarizing the findings across IPCC Working Groups. This is a coarse approach: for example, we assign all publications of the year 2013 to the Fifth Assessment Report cycle even though the Working Group I contribution was already published that year. However, this pragmatic procedure is justifiable as we only want to show orders of magnitude that remain unaffected.

Our results show that the total number of new studies that had to be considered for the Second and Third Assessment Report was about 26,000. In the most recent years of analysis, this amount of new literature is published annually. This highlights the challenges for current global environmental assessments – in particular the IPCC with its precise mandate. New avenues need to be explored for dealing more systematically with this ‘literature explosion’ making the organization of the assessment process more complex. For example, bibliometric and scientometric methods need to be applied systematically during the scoping and assessment process of global environmental assessments. There is an increasing dependence on synthesis efforts within the research community that can be built upon within the assessment process. In many communities – particularly the social sciences – such meta-analytical approaches are still underdeveloped.

Table S-8.4 Data on climate change literature

Year	Number of Publications	New literature for IPCC Assessments
1991	1,442	Second Assessment Report: 6,918
1992	1,650	
1993	1,907	
1994	1,919	
1995	2,333	Third Assessment Report: 18,718
1996	2,729	
1997	2,989	
1998	3,166	
1999	3,589	
2000	3,912	
2001	4,429	Fourth Assessment Report: 35,064
2002	4,810	
2003	5,248	
2004	6,014	
2005	6,863	
2006	7,700	
2007	9,738	Fifth Assessment Report: 122,659
2008	12,009	
2009	14,113	
2010	16,824	
2011	19,796	
2012	23,255	
2013	26,924	
2014	28,651	Sixth Assessment Report ↓

C) Background on the challenges and stakeholder engagement

Substantiating the three challenges

Although contemporary GEAs are facing many more challenges, we claim that the three challenges presented in the main paper belong to the most important and profound ones for contemporary, solution-oriented GEAs facing wicked problems.[42] This claim is based on both empirical and theoretical grounds. The empirical evidence inter alia stems from 99 semi-structured expert interviews on challenges and opportunities for contemporary GEAs, conducted as part of a larger research project on GEAs[43] that underlies the commentary. The interviewees highlighted particularly these three challenges. The empirical evidence cited in the commentary furthermore includes

[42] While GEAs might be better suited to address wicked problems than other science-policy-society platforms (see main text at the beginning), the wicked problems also imply severe challenges and limitations for GEA processes, including the impossibility to provide a consensus on policy options and pathways.

[43] See Acknowledgements in the main paper as well as http://www.mcc-berlin.net/en/research/cooperation/unep.html. The interviews and their method are described, for instance, in Garard and Kowarsch, 2017. The interviews (55 min on average) were conducted 2013–2015 with authors, producers and policymakers involved in the process and production of GEO-5, IPCC WGIII AR5, and a few other GEAs, as well with noninvolved intended GEA target audience. The interviews were analyzed using Grounded Theory Analysis methodology in Max QDA software, with iterative coding employed, following the guidance of Strauss and Corbin (1998).

relevant observations of GEA processes published by experienced assessment practitioners.

Moreover, also the theoretical and conceptual literature on GEAs strongly supports our selection of the challenges. While the specific characterization of these three problems as major challenges for contemporary GEAs in their current political context (i.e., the evolving governance landscape) is relatively new, core aspects of each of these challenges have been discussed before in the literature, usually in more generic terms.

For instance, as Kowarsch and Jabbour (2017) explain in more detail, the first of the three challenges identified in our commentary is basically about the 'salience' (in terms of the need for addressing those aspects that are highly relevant to decision-making processes) as well as the scientific 'credibility' (i.e., rigor and soundness) of policy evaluation; the second challenge is mainly about (civic) 'legitimacy' issues; and the third challenge is related to GEA influence overall, as a function of credibility, legitimacy and salience together. These concepts of 'credibility,' 'legitimacy' and 'salience' (including their trade-offs), which are largely compatible with our analysis, have been introduced and explained by the seminal Harvard GEA project[44] (e.g., Mitchell et al., 2006; Farrell and Jäger, 2006) in terms of widely accepted criteria for GEA influence. However, more specific recommendations for different contemporary GEAs are required that take into account the evolving governance landscape and the trade-offs between the three criteria. In this sense, our synthesis of promising options for solution-oriented GEAs to address the challenges identified contributes to the further development of the basic Harvard idea for GEA design into more specific recommendations for contemporary, solution-oriented GEAs.

Beyond Mitchell et al. (2006) and related publications, different strands of the existing theoretical literature regard the first challenge as highly important: (1) literature on the complexity of wicked policy issues (e.g., Rittel and Webber, 1973; Carley and Christie, 2000: 156; Head, 2008); (2) literature on the challenge of true interdisciplinarity and on the integration of scientific results into a common framework (e.g. Victor 2015); as well as (3) literature on the rapid growth of literature and the lacking knowledge aggregation particularly in the peer-reviewed social-science literature (e.g. Elsevier, 2016; Minx et al., 2017).

The second challenge is about integrating diverse and divergent viewpoints. While this can and actually has resulted in very practical challenges for GEA processes (for example, as highlighted in the main text with regards to the IAASTD), it also relates to broader debates over the politics of knowledge exchange and integration (Scoones, 2009), and to GEAs providing deliberative learning platforms at the international science-policy-society interface (Miller and Erickson, 2006; Kowarsch et al., 2016). The politics inherent in the exchange of knowledge is a central feature of any GEA process, which brings together a diversity of actors in order to assemble and synthesize available scientific and other knowledge (Scoones, 2009; Kowarsch et al., 2016). These diverse actors come from different disciplinary backgrounds but also hail from different parts of

[44] See http://www.hks.harvard.edu/gea/, accessed 05 Jan 2017.

the world, hold different institutional affiliations, and operate at different scales. Such a diverse group also implies a diversity of worldviews inter alia with regards to problem framing, judging the impacts of these problems, and assessing and prioritizing potential solutions pathways as well as more precise policy instruments. Bringing together these actors and integrating their often-divergent viewpoints through deliberation and reasoning together over the course of an assessment process is thus one of the major opportunities as well as a central challenge of GEAs (Miller and Erickson, 2006). As these enterprises become increasingly inclusive (as can be observed, for example, in the ambitious plans to engage with stakeholders in the IPBES process, Díaz et al., 2015) addressing this challenge will become increasingly important. Politics of knowledge may in fact often inhibit accommodating divergent normative viewpoints. Even if diverse stakeholders are brought together, that does not mean they participate in knowledge production on equal terms: there are important knowledge and power imbalances. This is particularly evident between state and non-state actors, or scientific knowledge vs indigenous knowledge (Obermeister, 2017), or natural sciences vs. social sciences. In fact, intergovernmental settings typically limit non-state stakeholders' agency because governments are often not willing to share power and authority. This is the case for the IPCC and has been observed for the IPBES too (Esguerra et al., 2017). Also, several authors have discussed the difficulties of engaging non-scientific stakeholders in scientific knowledge production and related tensions (van der Hel, 2016; Klenk et al., 2015).

The third challenge, i.e., the issue of increasing the influence of GEAs in the evolving governance landscape, is highlighted in more generic terms inter alia by Shulock (1999), Schreurs et al. (2001), Victor (2015), Posner et al. (2016) and Riousset et al. (2017). Since GEAs are usually intended to play a significant role in public policy processes, and since policy influence is generally hard to measure and dependent on various factors (many of which are beyond the control of GEA processes), facilitating outcomes and impact is a relatively natural challenge for GEAs. Riousset et al. (2017) highlight that the Social Learning Group (2001) and the Harvard GEA project pioneered research into the role played by scientific assessments produced by international institutions in attention cycles on global environmental risks, while some later publications have criticized their seminal findings for not adequately capturing the "*dynamic, continuous and multi-directional interactions between science, policy and society*" (Sarkki et al., 2015) in science-policy-society interfaces. The evolving governance landscape with its diversity of actors and lacking consensus (as characterized in the main text) increases this challenge.

Who is a stakeholder

The term 'stakeholder' can be broadly understood to refer to any individual affected by problems covered in a GEA, their impacts, or the solutions explored (for example through reference to the 'all affected' principle discussed by Goodin, 2008, and many others). Theoretically, this could include every person on the planet and even future generations. However, in such a large-scale process as a GEA, it is functionally impossible to engage with everyone who could potentially be considered a stakeholder given this broad definition.

As with any large-scale policy advisory process, a certain degree of representation is required in order to render deliberation and organization practically feasible given the transaction costs of communication. In light of the need to somehow reduce the number of stakeholders, the concept of relevant stakes becomes important in determining criteria to identify who are the most relevant stakeholders to engage. Criteria can be based on the objectives for engagement (Garard and Kowarsch, 2017), and the selection of stakeholders can in theory follow logically which groups or individuals are most crucial to achieving the objectives. Major stakeholder groups in solution-oriented GEA processes include, besides policymakers, business and industry, NGOs and civil society more broadly, GEA authors and users, etc.

Objectives for engaging with stakeholders

There is a huge diversity of potential objectives for engaging with stakeholders in a GEA process, which can include everything from the official objectives for engagement in the entire process distributed by the convening institution to the objectives held by individual participants for particular meetings. Drawing from the work of Garard and Kowarsch (2017), we will briefly describe four prominent objectives for stakeholder engagement in GEAs from the literature.

1. Stakeholders can provide diverse sources of information to a GEA process, contributing inter alia to the design and content development of a GEA. This can include input from a variety of scientific disciplines (Norgaard, 2008; Díaz et al., 2015), from decision makers (Reed, 2008), as well as from representatives of a broader diversity of viewpoints and knowledge systems (Berkes et al., 2006).
2. Engaging with stakeholders can increase the efficacy of communication and outreach of a GEA by ensuring the outputs and both relevant and comprehensible to target audiences (Mitchell et al., 2006; Field and Barros, 2015).
3. Stakeholder engagement can encourage a dialogue between diverse actors (including a fair dialogue between developed and developing countries), which can in turn build trust, enable learning, and ensure that outputs are based on rational argumentation and a plurality of viewpoints (Berkes et al., 2006; Stirling, 2008).
4. Engagement with stakeholders can increase their sense of ownership or buy-in to the assessment process and report, which in turn can increase the likelihood that they will use GEA outputs (Mitchell et al, 2006; Field and Barros, 2015).

Stakeholders can and should contribute to the content but also the objectives and design of GEA processes (as observed, for example, in the extensive stakeholder consultations which contributed to decisions on the IPBES conceptual framework, Díaz et al., 2015); appropriate protocols and institutions can facilitate the integration of a broader diversity of viewpoints into decisions taken on the objectives and design of GEA processes in their earliest stages.

References

Berkes, F., Reid, W.V., Wilbanks, T.J. and Capistrano, D. (2006). Conclusion: Bridging Scales and Knowledge Systems. In: W.V. Reid et al. (eds.). *Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment.* Washington, D.C.: World Resources Institute, pp. 315–331.

Carley, M. and Christie, I. (2000). *Managing Sustainable Development*. London: Earthscan.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., et al. (2015). The IPBES conceptual framework – connecting nature and people. *Current Opinion in Environmental Sustainability* 14: 1–16.

Elsevier (2016). *Sustainability Science in a Global Landscape*. A Report. Available online: https://www.elsevier.com/research-intelligence/research-initiatives/sustainability-2015.

Esguerra, A., Beck, S. and Lidskog, R. (2017). Stakeholder Engagement in the Making: IPBES Legitimization Politics. *Global Environmental Politics*, 17(1): 59–76.

Farrell, A.E. and Jäger, J. (2006). *Assessments of Regional and Global Environmental Risks. Designing Processes for the Effective Use of Science in Decisionmaking*. Danvers, MA: RFF Press Book.

Field, C.B. and Barros, V.R. (2015). Added value from IPCC approval sessions. *Science* 350(6256): 36.

Garard, J. and Kowarsch, M. (2017). If at first you don't succeed: Evaluating stakeholder engagement in global environmental assessments. *Environmental Science and Policy* (Special Issue on Solution-Oriented GEAs: Opportunities and Challenges) 77:235–243.

Goodin, R.E. (2008). *Innovating Democracy: Democratic Theory and Practice After the Deliberative Turn*. Oxford: Oxford University Press.

Grieneisen, M. and Zhang, M. (2011). The current status of climate change research. *Nature Climate Change* 1(2): 72–73.

Head, B.W. (2008). Wicked problems in public policy. *Public Policy* 3(2): 101–118.

Jabbour, J. and Flachsland, C. (2017). 40 years of global environmental assessments: a retrospective analysis. *Environmental Science and Policy* (Special Issue on Solution-Oriented GEAs: Opportunities and Challenges).

Klenk, N.L., Meehan, K., Pinel, S.L., Mendez, F., Lima, P.T. and Kammen, D.M. (2015). Stakeholders in Climate Science: Beyond Lip Service? *Science* 350(6262): 743–44.

Kowarsch, M. and Jabbour, J. (2017). Solution-oriented global environmental assessments: Opportunities and challenge. *Environmental Science and Policy* (Special Issue on Solution-Oriented GEAs: Opportunities and Challenges) 77: 187–192.

Kowarsch, M., Garard, J., Riousset, P., Lenzi, D., Dorsch, M., Knopf, B., Harrs, J.-A. and Edenhofer, O. (2016). Scientific assessments to facilitate deliberative policy learning. *Palgrave Communications* 2: 16092.

Miller, C. and Erickson, P. (2006). The politics of bridging scales and epistemologies: Science and democracy in global environmental governance. In: W.V. Reid et al. (eds.). *Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment.* Washington, D.C.: World Resources Institute, pp. 297–314.

Minx, J.C, Callaghan, M., Lamb, W.F., Garard, J. and Edenhofer, O. (2017). Learning about climate change solutions in the IPCC and beyond. *Environmental Science and Policy* (Special Issue on Solution-Oriented GEAs: Opportunities and Challenges) 77: 252–259.

Mitchell, R. B., Clark, W.C., Cash, D.W. and Dickson, N.M. (eds.) (2006). *Global Environmental Assessments: Information and Influence*. Cambridge, MA: MIT Press.

Norgaard, R. (2008). Finding hope in the Millennium Ecosystem Assessment. *Conservation Biology* 22: 862–869.

Obermeister, N. (2017). From Dichotomy to Duality: Addressing Interdisciplinary Epistemological Barriers to Inclusive Knowledge Governance in Global Environmental Assessments. *Environmental Science and Policy* 68: 80–86.

Posner, S.M., McKenzie, E. and Ricketts, T.H. (2016). Policy impacts of ecosystem services knowledge. *PNAS* 113(7): 1760–1765.

Reed, M.S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation* 141(10): 2417–2431.

Riousset, P., Flachsland, C and Kowarsch, M. (2017). Global Environmental Assessments: impact mechanisms. *Environmental Science and Policy* (Special Issue on Solution-Oriented GEAs: Opportunities and Challenges) 77: 260–267.

Rittel, H. and Webber, M. (1973). Dilemmas in a general theory of planning. *Policy Sciences* 4(2): 155–169.

Sarkki, S., Tinch, R., Niemelä, J., Heink, U., Waylen, K., Timaeus, J., Young, J. *et al.* (2015). Adding 'iterativity' to the credibility, relevance, legitimacy: A novel scheme to highlight dynamic aspects of science–policy interfaces. *Environmental Science and Policy* 54: 1–10.

Schreurs, M.A., Clark, W.C., Dickson, N.M. and Jäger, J. (2001). Issue attention, framing, and actors: an analysis of patterns across arenas. In: The Social Learning Group (ed.). *Learning to Manage Global Environmental Risks: A Comparative History of Social Responses to Climate Change, Ozone Depletion and Acid Rain*. Cambridge, MA: MIT Press, pp. 349–364.

Scoones, I. (2009). The politics of global assessments: The case of the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD). *The Journal of Peasant Studies* 36(3): 547–571.

Shulock, N. (1999). The paradox of policy analysis: If it is not used, why do we produce so much of it? *Journal of Policy Analysis and Management* 18(2): 226–244.

The Social Learning Group (ed.) (2001). *Learning to Manage Global Environmental Risks: A Comparative History of Social Responses to Climate Change, Ozone Depletion and Acid Rain*. Cambridge, MA: MIT Press.

Stirling, A. (2008). "Opening up" and "closing down": Power, participation, and pluralism in the social appraisal of technology. *Science, Technology, & Human Values* 33(2): 262–294.

Strauss, A. and Corbin, J. (1998). *The Basics of Qualitative Research.* Thousand Oaks: Sage Publications.

van der Hel, S. (2016). New Science for Global Sustainability? The Institutionalisation of Knowledge Co-Production in Future Earth. *Environmental Science and Policy* 61: 165–175.

Victor, D. (2015). Climate change: Embed the social sciences in climate policy. *Nature* 520(7545): 27–29.

8.4 Acronyms and definitions

All acronym and definitions are adapted from Allwood et al. (Allwood et al., 2014):

Adverse side-effects: The potential negative effects that a policy/measure aimed at one objective might have on other objectives, without yet evaluating the net effect on social welfare.

Aerosol: A suspension of airborne solid (primary PM) or liquid particles (secondary PM from gaseous precursors) that may influence climate in several ways.

Bioenergy and Carbon Dioxide Capture and Storage (BECCS): The application CCS technology to bioenergy conversion processes. Depending on the total lifecycle emissions, BECCS has the potential for net CO_2 removal from the atmosphere.

Traditional biomass: Biomass (e.g. fuelwood, charcoal, agricultural residues, animal dung) used with 'traditional' technologies such as open fires for cooking, rustic kilns and ovens for small industries.

Black carbon (BC): Aerosol species, also called soot, mostly formed by incomplete fuel combustion causing a warming effect by absorbing heat into the atmosphere.

Carbon dioxide (CO_2): A naturally occurring gas and by-product of burning fossil fuels and biomass, of land use changes and of industrial processes – the principal anthropogenic GHG.

Carbon Dioxide Capture and Storage (CCS): A process in which CO_2 from industrial and energy-related sources is captured, conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere.

CO_2-equivalent concentration (CO_2eq): The concentration of CO_2 that would cause the same radiative forcing as a given mixture of GHGs, aerosols, and surface albedo changes.

Co-benefits: The potential positive effects that a policy/measure aimed at one objective might have on other objectives, without yet evaluating the net effect on social welfare.

Cost-effectiveness analysis (CEA): A tool based on constrained optimization for comparing policies designed to meet a prespecified target.

Cost-benefit analysis (CBA): Monetary measurement of all negative and positive impacts associated with a given policy.

Energy intensity (EI): The ratio of energy use to economic or physical output.

Greenhouse gas (GHG): Gaseous constituents of the atmosphere (natural and anthropogenic), which absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted, e.g. by the earth's surface.

Gross domestic product (GDP): The sum of gross value added by all producers in an economy (plus any taxes and minus any subsidies not included in the value of the products) for a given period, normally one year.

Mitigation (of climate change): Reducing the sources or enhancing the sinks of GHGs; or reducing other substances that contribute directly or indirectly to limiting climate change, e.g. PM emissions.

Mitigation measures are technologies, processes or practices that contribute to mitigation.

Mitigation pathways: The trajectory to meet a given mitigation goal that implies a set of economic, technological, and behavioural changes.

Nitrogen oxides (NO_x): Any of several oxides of nitrogen.

Particulate matter (PM): Very small solid particles from solid fuel combustion which cause adverse health effects (particularly < 10 nanometres, PM_{10}) and can directly alter the radiation balance.

Precursors: Atmospheric compounds that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Radiative forcing: The change in the net radiative flux (in Wm^{-2}) at the tropopause due to a change in an external driver of climate change, e.g. changing CO_2 concentrations.

Short-lived climate pollutant (SLCP): Air pollutant emissions that have a warming influence on climate and have a relatively short lifetime in the atmosphere (a few days to a few decades).

Sink: Any process, activity or mechanism that removes a GHG, an aerosol, or a precursor of a GHG or aerosol from the atmosphere.

Sulphur dioxide (SO_2)

Sustainable development (SD): Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Traditional biomass: fuelwood, charcoal, agricultural residues, and animal dung used with traditional technologies, e.g. open fires for cooking, rustic kilns, and ovens for small industries.

Working Group III Contribution to the IPCC Fifth Assessment Report (WGIII AR5)

9 Statement of contribution

The chapters of this thesis are the result of collaborations between the candidate and his advisor, Prof. Dr. Ottmar Edenhofer, and other colleagues. The candidate has made significant contributions to the contents of all seven chapters, from conceptual design to writing. Chapters 1 and 7 were outlined and written by the candidate. The authors of all remaining chapters, including the Annex 8.3, are indicated in the table below (with the name of the candidate in bold letters) and their respective contributions are detailed below.

Chapter	Publication reference
#2	Edenhofer, O., Kadner, S., **von Stechow, C.**, Minx, J. (2015). Beyond the 2°C limit: Facing the economic and institutional challenges, in: Barrett, S., Carraro, C., de Melo, J. (Eds.), *Towards a Workable and Effective Climate Regime*. CEPR Press, London, pp. 49–68. Postprint. https://cepr.org/chapters/beyond-2degc-limit-facing-economic-and-institutional-challenges
#3	Creutzig, F., **von Stechow, C.**, Klein, D., Hunsberger, C., Bauer, N., Popp, A., Edenhofer, O. (2012). Can Bioenergy Assessments Deliver? *Economics of Energy & Environmental Policy* **1**: 65–82. Postprint. https://doi.org/10.5547/2160-5890.1.2.5
#4	Edenhofer, O., Kadner, S., **von Stechow, C.**, Schwerhoff, G., Luderer, G. (2014). Linking Climate Change Mitigation Research to Sustainable Development, in: Atkinson, G., Dietz, S., Neumayer, E., Agarwala, M. (Eds.), *Handbook of Sustainable Development*. Edward Elgar. 2nd Ed., Cheltenham, UK, pp. 476–499. Preprint. https://doi.org/10.4337/9781782544708.00044
#5	**von Stechow, C.**, McCollum, D., Riahi, K., Minx, J.C., Kriegler, E., van Vuuren, D.P., Jewell, J., Robledo-Abad, C., Hertwich, E., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N.K., Bollen, J., Ürge-Vorsatz, D., Edenhofer, O. (2015). Integrating global climate change mitigation goals with other sustainability objectives: A synthesis. *Annual Review of Environment and Resources* **40**: 363–394. Postprint. https://doi.org/10.1146/annurev-environ-021113-095626
#6	**von Stechow, C.**, Minx, J.C., Riahi, K., Jewell, J., McCollum, D.L., Callaghan, M.W., Bertram, C., Luderer, G., Baiocchi, G. (2016). 2°C and SDGs: united they stand, divided they fall? *Environmental Research Letters* **11**: 34022. Postprint. https://doi.org/10.1088/1748-9326/11/3/034022
#8.3	Kowarsch, M., Jabbour, J., Flachsland, C., Kok, M.T.J., Watson, R., Haas, P.M., Minx, J.C., Alcamo, J., Garard, J., Riousset, P., Pintér, L., Langford, C., Yamineva, Y., **von Stechow, C.**, O'Reilly, J., Edenhofer, O. (2017). Commentary: A road map for global environmental assessments. *Nature Climate Change* **7**, 379–382. Postprint. https://doi.org/10.1038/nclimate3307

Chapter 2: The author contributed to the literature review and to the revision of the article based on a previous version. The author contributed various text parts and revisions. In particular, he helped design the last section of the article and wrote the corresponding text parts.

Chapter 3: The author contributed to the literature review and developed a former version of the final article together with David Klein and Ottmar Edenhofer. The author contributed various text parts and revisions. In particular, the author evaluated the existing bioenergy assessment, including contributing to the design and content of the above table, and wrote the corresponding text parts.

Chapter 4: The author contributed to the conceptual design, handling and writing of the article. In particular, he conducted large parts of the literature review, helped develop the welfare-theoretic framework, draw conclusions for policy evaluation in a multiple objectives framework, discuss the recent scenario literature and write and revise the corresponding text parts.

Chapter 5: The author is responsible for the conceptual design, handling and writing of the article. The literature review for the main article was performed by the author; the additional review in the supplemental material was performed by the co-authors and coordinated by the author. The development of the conceptual framework was supervised by Ottmar Edenhofer. The analysis uses scenario data from different integrated energy-economy-climate openly accessible through the IIASA Scenario Database. The author is solely responsible for the design of the figures and tables (except Figures 5.4 and 5.5), performing the literature review and writing the article with revisions by the co-authors, particularly David McCollum, Keywan Riahi, Jan C. Minx, Elmar Kriegler, Detlef van Vuuren and Jessica Jewells. Keywan Riahi, Ottmar Edenhofer and Jan C. Minx contributed to the framing of the research questions.

Chapter 6: The author is responsible for the conceptual design, handling and writing of the article. The analysis uses scenario data from different integrated energy-economy-climate openly accessible through the IIASA Scenario Database. The design and generation of the figures of the article and the Supplementary was performed jointly by the author and Max Callaghan. The author is solely responsible for the literature review. the choice and design of the indicators and writing the article and the Supplementary Information with revisions by the co-authors, particularly Jan C. Minx, Keywan Riahi, Jessica Jewells and David McCollum. Jan C. Minx contributed to the framing of the research questions.

Chapter 8.3: The author contributed to the data collection and analysis which underlies the findings as well as Figure 8.1 (as laid out in more detail in Supplementary Material A). The author was an important asset in sharing his experience with the processes and theoretical underpinnings of IPCC assessments and he also contributed to revising and editing the text through multiple iterations with other co-authors. He also contributed to the clarification and definition of key technical terms in the field of sustainability.

10 Tools and resources

If not stated otherwise, all text, tables, and figures were produced with Microsoft Office Word, Excel, and PowerPoint 2003/2010. References were added using the reference manager Zotero. Additional tools and resources are detailed below.

Chapter 2: n/a

Chapter 3: MatLab

Chapter 4: ReMIND

Chapter 5: n/a

Chapter 6: R