Environmental impact assessment in energy-economy-climate models

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Contents

Abstract

Climate change is one of, if not the, most important issues faced by the global society in the 21st century. The effects of climate change are visible on all continents and oceans already today and a business-as-usual will lead to severe consequences on the earth system, the economy and public health. Keeping these risks in check, the international community signed the Paris Agreement, stating the goal to limit the global mean temperature rise at the end of the century to well below 2 °Celsius above pre-industrial levels pursuing efforts to limit it to 1.5°C. This is one of the first incidents of human kind acknowledging that the current development is not sustainable and the earth's limits would be reached in a time span of a few generation.

Achieving the Paris Agreement goals requires greenhouse gas emission net neutrality around mid century, implying a limited remaining greenhouse gas emission budget. This necessitates an unprecedented transformation of the energy system, land-use sector and, if economic development and energy demand are not decoupled, deprioritization of economic growth. However, the remaining emission budget is currently over-exploited by countries acting independently according to their own self-interest, free-riding on the mitigation efforts of the others, a case of the Tragedy of the Global Commons. In this context, climate change has also been called the biggest market failure since the emitters of greenhouse gases seldom face the associated cost.

In the absence of a price reflecting climate change impacts, climate policies are required. Policymakers establish policies to achieve the transformation, crucially informed by scenarios from integrated energy-economy-climate models. The common approach is to model economically optimal scenarios while constraining greenhouse gas emissions to meet a set radiative forcing target. This transformation intersects with other sustainability goals which can lead to positive, called co-benefits, or negative effects, called adverse side effects. However, the common approach lacks accounting for other co-benefits and adverse side effects associated with the infrastructure and the operation of the energy system. These include air pollution - public health effects, water–energy–land nexus and biodiversity conservation. Consequently, for a holistic sustainability assessment it is necessary to endeavour beyond an isolated consideration of greenhouse gas emissions as the unique metric.

The research question this dissertation is tackling is therefore: What are the co-benefits and adverse side effects of energy and climate policy?

The three main chapters assess this topic with different foci. The first chapter focuses on the specific consideration of one of the most important externality of the energy system, air pollution induced public health effects. In the second chapter a comprehensive life cycle based assessment of impacts for a subsystem, the electricity system in Germany, is performed. Here, the sustainability dimension is evaluated against the economic cost through a multi criteria optimization. Finally we do a comprehensive analysis of different global climate policy scenarios with the focus on the policy of a global coal exit.

Our main result is that the co-benefits of climate policy are in the same order of magnitude as the mitigation cost, if a comprehensive analysis is applied, confirming its relevance. Especially major emitters of greenhouse gas emissions such as India and China benefit the most from climate mitigation efforts, this can function as an early entry point for climate mitigation policies. In contrast to climate policies the human health and environmental co-benefits are local and intra-generational. This can help tackle the described Tragedy of the Global Commons of climate mitigation.

We show that renewable energies not only emit the lowest greenhouse gases they also outperform fossil fuel based technologies on most of the other sustainability criteria. However, our results show that the co-benefits consideration needs to be comprehensive as climate policies can lead to challenges for example in land-use and resource depletion that need further attention. We further show that including the whole life cycle and a system wide analysis are crucial as impacts are shifted from direct to indirect emissions and unintended substitution effects need to be accounted for.

Finally we give an outlook for future research directions which should mainly focus on a more detailed modeling of environmental and human health impacts as well as the question on how to integrate the impact assessment into the modeling of transition pathways.

Zusammenfassung

Der Klimawandel ist eine der, wenn nicht gar die wichtigste Herausforderung der Menschheit im 21. Jahrhundert. Die Auswirkungen des Klimawandels sind auf allen Kontinenten und Ozeanen bereits heute sichtbar und ein weiter wie bisher hätte schwerwiegenden Folgen für die Umwelt, Wirtschaft und öffentliche Gesundheit. Um diese Risiken in Schach zu halten, unterzeichnete die internationale Gemeinschaft das Pariser Übereinkommen, in dem sie sich darauf einigte, den globalen Anstieg der mittleren Temperatur bis zum Ende des Jahrhunderts auf deutlich unter 2°Celsius über dem vorindustriellen Niveau zu begrenzen und Anstrengungen zu unternehmen, um ihn auf 1,5°C zu begrenzen. Dies ist einer der ersten Ereignisse in der die Menschheit anererkennt, dass die gegenwärtige Entwicklung nicht nachhaltig ist und die Grenzen der Erde in einer Zeitspanne von wenigen Generationen erreicht werden würden.

Um die Pariser Ziele zu erreichen, muss um die Mitte des Jahrhunderts netto Neutralität von Treibhausgasen erreicht werden was ein verbleibendes Emissionsbudget impliziert. Dies erfordert eine beispiellose Transformation des Energiesystems, des Landnutzungssektors und, wenn wirtschaftliche Entwicklung und Energienachfrage nicht entkoppelt werden, die Entpriorisierung von Wirtschaftswachstum. Das verbleibende Emissionsbudget wird derzeit von Ländern übermäßig ausgeschöpft, die nach ihrem eigenen Eigeninteresse handeln und von Minderungsbemühungen der anderen profitieren, ein Fall der Tragödie der Global Commons. Folglich wird der Klimawandel auch als das größte Marktversagen bezeichnet, da die Emittenten von Treibhausgasen selten mit den damit verbundenen Kosten konfrontiert sind.

Dem Marktversagen zu begegnen erfordert das Eingreifen der Politik. Die politischen Entscheidungsträger legen dazu Maßnahmen fest, die auf detaillierten Abschätzungen ihrer Auswirkungen basieren. Dabei werden sie durch Szenarienanalysen von Integrated Assessment und Energiesystemmodellen informiert. Der gängige Ansatz besteht darin, wirtschaftlich optimale Szenarien zu modellieren und gleichzeitig die Treibhausgasemissionen zu begrenzen, um ein festgelegtes Erwärmungsziel zu erreichen.

Die Dekarbonisierung unseres Wirtschaftens überschneidet sich aber mit einer Vielzahl anderen Nachhaltigkeitszielen, was zu Zusatznutzen oder negativen Effekten führen kann. Dem gängigen Ansatz fehlt es jedoch an der Berücksichtigung dieser Zusatznutzen und Nebenwirkungen im Zusammenhang mit der Infrastruktur und dem Betrieb des Energiesystems. Dazu gehören unter anderem die durch Luftverschmutzung verursachten Auswirkungen auf die öffentliche Gesundheit, der Nexus zwischen Wasser, Energie und Land und der Schutz der biologischen Vielfalt. Für eine ganzheitliche Nachhaltigkeitsbewertung ist es daher notwendig, über eine isolierte Betrachtung der Treibhausgasemissionen

als alleinige Kennzahl hinauszugehen.

Die Forschungsfrage, der sich diese Dissertation widmet, ist daher: Was sind die Zusatznutzen und negativen Effekte von Energie- und Klimapolitik?

Die drei Hauptkapitel beleuchten diese Themenfeld mit unterschiedlichen Schwerpunkten. Das zweite Kapitel konzentriert sich auf die spezifische Berücksichtigung einer der wichtigsten Externalität des Energiesystems, durch Luftverschmutzung induzierte Auswirkungen auf die öffentliche Gesundheit. Im dritten Kapitel wird eine umfassende lebenszyklusbasierte Bewertung der Auswirkungen für ein Subsystem, das Elektrizitätssystem in Deutschland, durchgeführt. Die Nachhaltigkeitsdimension wird hierbei durch eine multikriterielle Optimierung mit den wirtschaftlichen Kosten verglichen. Schließlich führen wir eine umfassende Analyse verschiedener globaler klimapolitischer Szenarien durch, wobei der Schwerpunkt auf der Politik eines globalen Kohleausstiegs liegt.

Unser Hauptergebnis ist, dass die Zusatznutzen der Klimapolitik bei einer umfassende Analyse in der gleichen Größenordnung liegen wie die Minderungskosten. Vor allem große Emittenten von Treibhausgasemissionen wie Indien und China profitieren am meisten von den Bemühungen um den Klimaschutz, dies kann als früher Einstieg in Klimaschutzpolitik dienen. Im Gegensatz zur Klimapolitik sind die Vorteile für die menschliche Gesundheit und die Umwelt lokal und zeitnah. Dies kann dazu beitragen, die beschriebene Tragödie der Global Commons von Klimapolitik zu bewältigen.

Wir zeigen weiter, dass erneuerbare Energien nicht nur die niedrigsten Treibhausgasemissionen ausstoßen, sondern auch einen geringere Auswirkung auf die meisten anderen Nachhaltigkeitskriterien als auf fossilen Brennstoffen basierenden Technologien haben. Unsere Ergebnisse zeigen jedoch, dass die Betrachtung der Zusatznutzen umfassend sein muss, da Klimapolitik zu Herausforderungen zum Beispiel bei der Landnutzung und der Ressourcenverknappung führen kann, die weitere Aufmerksamkeit erfordern. Wir zeigen ferner, dass die Einbeziehung des gesamten Lebenszyklus und eine systemweite Analyse entscheidend sind, da die Auswirkungen von direkten auf indirekte Emissionen verlagert werden und unbeabsichtigte Substitutionseffekte berücksichtigt werden müssen.

Schließlich geben wir einen Ausblick auf zukünftige Forschungsfelder, die sich vor allem auf eine detailliertere Modellierung der Auswirkungen auf die Umwelt und die menschliche Gesundheit sowie auf die Frage konzentrieren sollten, wie die Folgenabschätzung in die Modellierung von Transformationspfaden integriert werden kann.

Chapter 1

Introduction

1.1 Climate Change and sustainable development

For most of human kind's history, the energy demand per capita stagnated and was supplied by traditional biomass. In the 18^{th} to the 19^{th} century, the first industrial revolution kick-started an exponential growth in the global energy demand which lasts until today. This surge in energy demand is fueled by a growing world population and economic growth and mostly supplied by fossils fuels. (see Fig. 1.1)

The combustion of fossil fuels is characterized by the release of greenhouse gases (GHG) of which carbon dioxide (CO_2) makes up most of anthropogenic emissions. When burning traditional biomass the released CO_2 is equal to the captured CO_2 stored in the biomass growing phase. In contrast, fossil fuel CO_2 was formed millions of years ago and it's combustion therefore leads to net positive emissions. Consequently, the global fossil fuel related GHG emissions rose analogously to the fossils fuel use, see Fig.1.2. About half of these anthropogenic GHG emissions are absorbed by natural sinks such as the oceans, soils and vegetation. Nevertheless the CO_2 concentration in the atmosphere rose from an average of about 200 ppmv [1] of the 400,000 pre-industrial years[2] to more than 400 ppmv today, see Fig. 1.2.

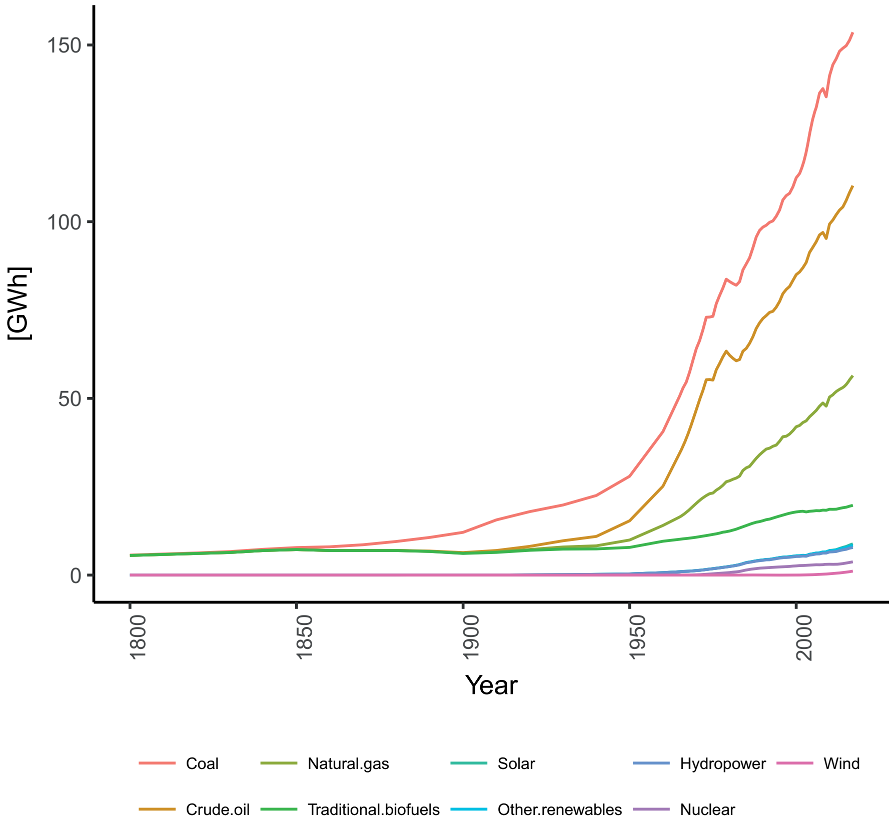
GHGs are active in the infrared part of the electromagnetic spectrum, causing the greenhouse effect. Rising GHG concentrations in the atmosphere cause an imbalance in sunlight absorbed by the earth and energy radiated back to space which leads to an increase in radiative forcing, causing global warming.

In the special report on 1.5°C (13) the Intergovernmental Panel on Climate Change (IPCC) estimated that "human activities [...] have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C." (see Fig. 1.3 for the annual temperature anomalies realative to the 1951-1980 base period means.) Additionally, "since the 1970s, most land regions have been warming faster than the global average[...]. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population lives in regions that have already experienced warming in at least one season that is greater than 1.5°C above prein-

[1] Russian Vostock station, the deepest ice core ever recovered, reaching a depth of 3,623 m. Data available at `https://cdiac.ess-dive.lbl.gov/ftp/trends/co2/vostok.icecore.co2`

[2] 2342 to 417,160 years BP

Figure 1.1: |Global primary energy consumption. Data from `https://ourworldindata.org/grapher/global-primary-energy`.



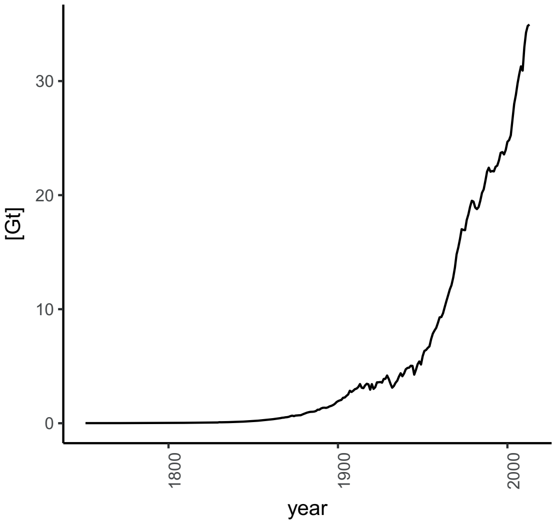
dustrial levels." The IPCC further states in the Fifth Assessment Report (12) that "Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies." (see Fig. 1.2)

Continuing on the current emission pathway, with only moderate climate policies in place, will result in ever increasing GHG emissions. In this "business-as-usual" scenario, the global mean temperature is projected to surpass the 1.5°C mark already around 2030 and result in an estimated temperature increase of more than 3°C by the end of the century. This will lead to an increased risk for impacts ranging from a loss of unique ecosystem like warm-water corals and more frequent extreme weather events illustrated in Fig. 1.4.

As the IPCC shows in the special report on 1.5°C (13), already today there are impact on all continents and oceans. The evidence for these "observed climate change impacts is strongest and most comprehensive for natural systems. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality [...]. Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change [...]. Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences."

Figure 1.2: |Global Carbon Dioxide emissions and concentration.

(a) |Global Carbon Dio 2342 to 417,160 years BPxide emissions from fossil-fuel burning, cement manufacture, and gas flaring. Data from the Carbon Dioxide Information Analysis Center `cdiac.ess-dive.lbl.gov/`.



(b) |Carbon Dioxide concentration in air. Monthly atmospheric Carbon Dioxide Dry Air Mole Fractions from quasi-continuous measurements at Barrow, Alaska. Data available at `esrl.noaa.gov/`. Dashed line indicates the min and max of the Russian Vostock station, the deepest ice core ever recovered, reaching a depth of 3,623 m. Data available at `https://cdiac.ess-dive.lbl.gov/ftp/trends/co2/vostok.icecore.co2`.

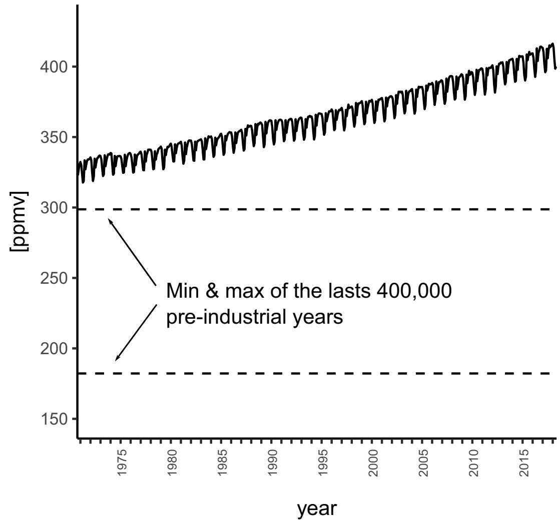
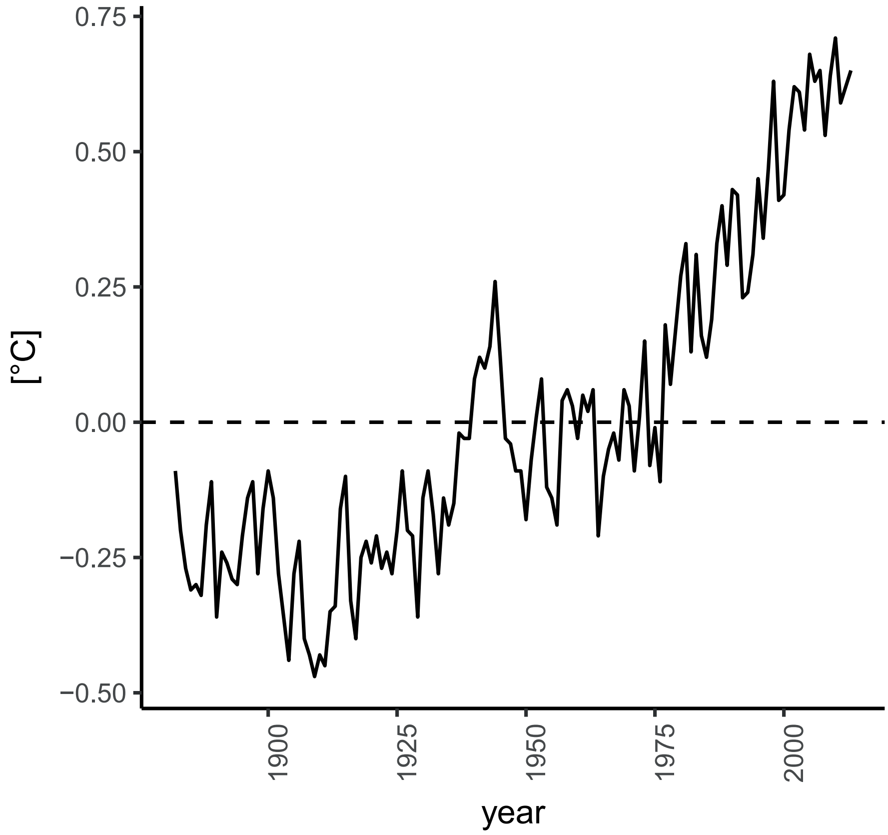


Figure 1.3: |Global annual temperature anomalies. Land and Ocean area temperature anomalies relative to the 1951-1980 base period means. data from the Carbon Dioxide Information Analysis Center `cdiac.ess-dive.lbl.gov/`.



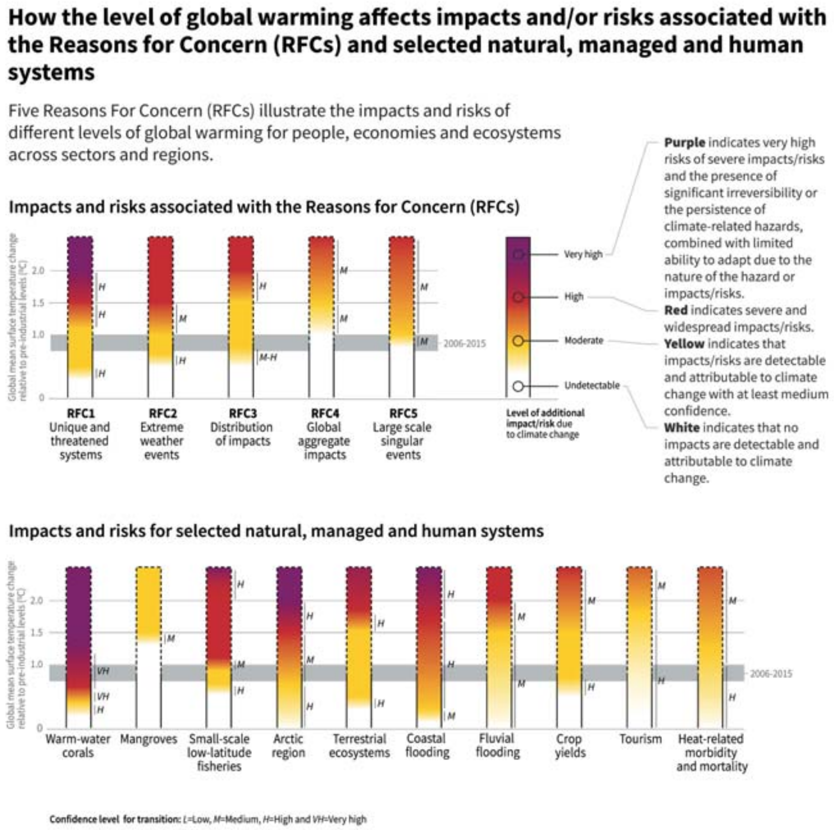
The rising temperatures and their effect on the earth system will also have impacts on the economic development. As pointed out by the World Bank (30), climate change impacts are a threat to economic development and the eradication of hunger and poverty. Consequently, conflicts for land and water as well as extreme weather events will lead to an increase in forced migration.

Besides these impacts, research points towards the non-linearity of certain impact channels, so called tipping points (15). When crossing these thresholds, cascading effects might be triggered that result in developments that are only reversible over a long time span such as the melting of the Greenland ice sheet and the Permafrost as well as damage to the Boreal forests.

The additional warming induced by an impulse emission of CO_2 stays approximately constant over many centuries, which implies a limited budget of remaining emissions to achieve a Paris compliant scenario (13). This limited atmospheric disposal space for greenhouse gases fulfills the defining criteria of a global common good. As a global common good, it is subject to *the Tragedy of the (Global) Commons* (16; 3): A common good is over-exploited by individuals acting independently according to their own self-interest, free-riding on the mitigation efforts of the others [3]. In the specific context of climate

[3] Following (1) free-riding occurs when a party receives the benefits of a public good without contribut-

Figure 1.4: |Qualitative assessment of impact and risk of global warming. Assessment of the the impact and risk of different levels of global warming on five integrative reasons for concern. Expert judgment based on the current literature. Adapted [reprinted] from "IPCC, “Global warming of 1.5°C An IPCC 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, 2018".



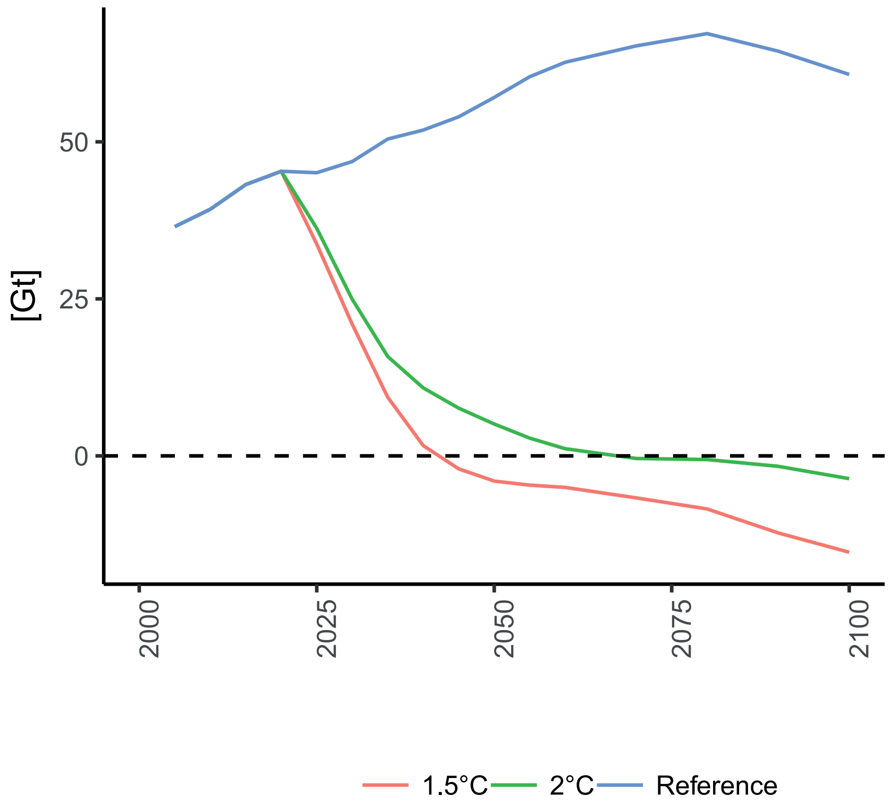
change, free-riding countries benefit from climate mitigation efforts of other countries but don’t contribute "appropriately" to the cost (1). Moreover, climate policy comes with the additional challenge of inter-generational free-riding, since consumption benefits of lax climate policy are enjoyed today, at the expense of future generations. A combination of the two is the historic free-riding of the last three (industrialized) 1st world generations on the climate budget of global future generations. Therefore, climate change is also called the biggest market failure.

Tackling this market failure and keeping the earth in a "safe operating space", the global community set the target in the Paris Agreement to limit the global mean temperature rise above preindustrial levels to well below 2°C pursuing efforts for 1.5°C by end of the century. The Paris Agreement is characterized by individual nationally determined contributions (NDCs), in which all countries report their bidecadal planned contributions to the overall reduction goals. However, these contributions are non-binding and there is no sanctioning mechanism to enforce countries to set NDCs or meet their targets. The agree-

ing to the costs.

ment relies on the "name and shame" principle which is informed by a global stock-take. Although, the contributions should be "ambitious", "represent a progression over time" and suitable to "achieving the purpose of this Agreement", the current NDCs proved inadequate to lower emissions to a Paris compliant emission pathway (25). On the contrary, the emissions are rising and a "peak CO_2" was still not reached on a global level. As Fig. 1.5 illustrates for CO_2, a 1.5°C pathway implies immediate and deep emission reductions and net neutrality around 2050. The amount of necessary negative emissions in the second half of the century is determined by how much the temperature target is overshot and the residual emissions of CO_2 and other GHG.

Figure 1.5: |Global Carbon dioxide emission pathways. Emission pathways to achieve 1.5°C and 2°C end of the century global warming target compared to a business as usual Reference scenario. The dashed line indicates net neutrality. Own calculation of the REMIND model.



1.2 Holistic climate change mitigation

Figure 1.6: |Sustainable Development Goals. Adapted [reprinted] from `https://www.un.org/sustainabledevelopment/`

As elaborated up-on in the previous chapter, an unmitigated climate change would have serious consequences on the environment, the economy and the public health. Therefore, sustainable development is only possible if climate change is limited. Thus climate change and sustainable development are deeply intertwined. This becomes apparent when we look at the sustainability goals put forward by the UN succeeding the Millennium Development Goals, see Fig. 1.6. They are comprised of 17 overall goals and 169 corresponding targets.

The deep transformation necessary to achieve climate change mitigation provides the opportunity to foster sustainable development or, when poorly managed has potential negative consequences. The phase-out of fossil fuel combustion for example can help tackling the air pollution crisis in Asia or the large-scale deployment of bioenergy can shorten food supply and have impacts on biodiversity (2; 19).

At the same time, not considering sustainable development goals can prevent effective climate policy implementation. Economic development (SDG 1), food supply (SDG 2), education (SDG 4) as well as strong institutions (SDG 16) and global co-operations (SDG 17) are key factors for strong climate mitigation. Or, the lack of those can jeopardize climate goals. Therefore, it is crucial to analyse climate mitigation policies in an integrated framework, quantifying the co-benefits and adverse side effects.

Tackling climate change requires intervention by policy makers through climate change mitigation policies. It is established that the economic optimal policy would be a CO_2 price, however, this proofed hard to implement and only an estimated 20 % of global CO_2 emissions is priced at all and only 5 % Paris Agreement consistent (23). There is a wide array of other policies in place, they reach from feed-in tariffs for low emission technologies to technological standards, demand side management and research funding for CO_2 removal policies.

A climate or energy policy will always have effects other than on the intended objective. These effects are either called co-benefits when positive or adverse side effects when negative. A prominent example is the GHG emission reduction of bio-energy substitutions for gasoline which can have adverse side effects on land-use related biodiversity impacts. Co-benefits of electrifying mobility on the other hand are air quality improvements in urban areas and noise reductions. As stated above, co-benefits of climate policy concern most of the SDGs, especially environmental pollution and public health.

Therefore, a holistic assessment of climate policy considers systemic effects such as substitution and leakage effects as well as impacts from the whole life cycle and assessed a comprehensive spectrum of impact channels, facilitating a comprehensive assessment of co-benefits and adverse side effects. Recently, there are efforts to quantify non-GHG effects of climate change mitigation policies on air pollution (24), land-use (22; 5), and water (6; 20) as well as comprehensive assessments of the electricity system (17). However, a system wide holistic assessment of climate policy is still missing.

1.3 Thesis objective and outline

The co-benefits and adverse side effects from climate policies have not yet been quantitatively examined in an integrated comprehensive framework. The research question this dissertation is tackling is therefore: What are the co-benefits and adverse side effects of energy and climate policy? Guiding principles are:

(a) **Holistic assessment of climate mitigation scenarios and policies:** A holistic assessment of climate policy is necessary to answer key questions of the transformation to a low carbon future such as resource implications of electrified mobility, human health benefits of fossil fuel phase out and biodiversity implications of bioenergy deployment.

(b) **Specific assessment:** We model the relevant factors of the co-benefit and adverse side effect consideration as specific as necessary. For example socio-economic factors are crucial for the co-benefits of air quality improvements and exposure response relationships are non-linear. This requires a spatially explicit impact modeling as well as the consideration of socio-economic factors such as future population, demography and urbanization developments.

(c) **Life Cycle Assessment:** Renewable energy supply shifts the bulk of the emissions from direct, associated with combustion of fuels, to indirect, associated with the production of the energy infrastructure. Additionally, decarbonizing the energy supply has effects on the embodied emissions of every process and product in the economy. Therefore all stages of a life cycle need to be considered.

(d) **Comprehensive assessment:** A full picture of all impacts requires a comprehensive modeling capturing all relevant impact channels. We model the influence of climate policy as comprehensive as possible with a wide set of impact categories building on established models of the industrial ecology community.

(e) **System wide modeling:** As stated above, climate policies can have substitution and leakage effects. This requires a system wide analysis.

(f) **Integrated assessment:** We want to consider co-benefits and adverse side effects in an integrated framework. This is done by relating them in monetary terms to the associated policy cost or multi-objective assessment of cost and benefits.

The three main chapters have different foci reflecting these principles. The first chapter focuses on the specific consideration of the most important externality of the energy system, air pollution induced public health effects. In the second chapter a comprehensive life cycle based assessment of impacts for a subsystem, the electricity system in Germany, is performed. The sustainability dimension is evaluated against the economic cost through a multi criteria optimization. Finally we do a comprehensive analysis of different global climate policy scenarios with a focus on the comparison of cost and benefits.

1.4 Methodological approach

The exploration of possible futures is done with models that try to translate the relevant real world mechanisms and dynamics into computable numerical representations. We distinguish between partial, covering only a subsystem, and general equilibrium models, covering the whole system.

We use a highly detailed partial equilibrium model of the power sector in the 3nd chapter and a general equilibrium integrated assessment model REMIND in the 1st and 4th chapters.

Traditionally Energy-economy-climate models optimize welfare or minimize economic cost with the constraints of an emission budget and other climate mitigation or energy policies. Non-climate impacts are not considered or analyzed ex-post. In contrast to economic implications, the evaluation these societal and ecological impacts is often less straightforward and can involve sensible ethical questions, for example in regards to the monetary value of ecosystem services or human health as well as the unclear distribution of costs across different societal groups.

In integrated assessment models, frequently used to inform policy makers on climate mitigation pathways, there is recent research where single co-benefits are analysed, prominently air pollution (24; 29; 26) and water (20; 6). The energy-land nexus is well described by coupling integrated assessment models to land-use models, important because bioenergy plays a key role in decarbonizing the energy system (5; 14). A comprehensive modeling of non-economic and non-GHG impacts are rare but research emerged in recent years (2) especially for the power sector (17; 7; 8).

The industrial economy community on the other hand has a long history of comprehensive assessments of impacts with a focus on products and their whole life cycle including up and down stream impacts.

Life Cycle Assessment is an established method to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. In principle the method is comprised of three matrices (see (10) for a detailed description of the computational background). The technology matrix describes the relationship of each process to each other, for example how much coal is used for one unit of electricity. The emission matrix connects each process to emissions into water, air and to land. Finally, the characterization matrix relates each emission to their impact on indicators according to the selected impact assessment method. We use the most established technology and emission database ecoinvent (28) comprised of about 17,000 interconnected processes. The translation of emissions into impact is performed with the ReCiPe method (9). These factors are calcualted utilizing a bundle of simplified models with the goal of aggregating the impacts to midpoint indicators, see Table 1.1. These midpoints can be aggregated according to their impact on the end points of human health, ecosystems and resources.

However, life cycle assessment is traditionally static and socio-economic developments or technological changes are not considered with the exception of a few studies emerging recently in the energy field (11; 21; 18; 4; 27).

Table 1.1: |RECIPE impact assessment indicators. Overview of the impact categories of the RECIPE method.

Human health
Global Warming - Human health
Stratospheric ozone depletion - Human health
Ionzing Radiation - Human health
Fine particulate matter formation - Human health
Photochemical ozone formation - Human health
Toxicity - Human health (cancer)
Toxicity - Human health (non-cancer)
Water consumption - human health
Terrestrial ecosystems
Global Warming - Terrestrial ecosystems
Photochemical ozone formation - Terrestrial ecosystems
Acidification - Terrestrial ecosystems
Toxicity - Terrestrial ecosystems
Water consumption - terrestrial ecosystems
Land use - occupation and transformation
Freshwater ecosystems
Global Warming - Freshwater ecosystems
Eutrophication - Freshwater ecosystems
Toxicity - Freshwater ecosystems
Water consumption -aquatic ecosystems
Marine ecosystems
Toxicity - Marine ecosystems
Eutrophication - Marine ecosystems
Resources
Mineral resource scarcity

Corresponding to the above mentioned foci of the different chapters we apply different models. The general concept is to broaden the cost and GHG emission focus of the energy-economy-climate models through coupling with impact assessment models. In the 2nd chapter we combine the energy-economy-climate model REMIND with a detailed modelling of air pollution human health impacts. Air pollution depends on sectors, the development of filter policy, but also on spatial explicit socio-economic trends such as population developments, demographic changes and urbanization. We translate the impacts on human health into cost and focus on Europe and China and India. The impact assessment is applied ex-post to welfare optimal climate mitigation scenarios.

The 3rd chapter focuses on a detailed description of the German power system. The energy-economy-climate model is formulated as a mixed integer linear programming problem with a technology rich representation of the capacity expansion and commitment in a temporally high detailed manner. We couple this to a detailed life cycle assessment based impact assessment of these technologies. The model is fully integrated and solved as a multi-objective optimization problem with total system cost and total impact as the two objectives.

Finally, in the 4th chapter, the energy-economy-climate model REMIND is combined with the detailed air pollution model and coupled to a comprehensive, prospective life cycle assessment based impact consideration. This framework is applied to assess the economic and environmental effects of a global coal exit.

Bibliography

[1] William J. Baumol. Welfare Economics and the Theory of the State. In *The Encyclopedia of Public Choice*, pages 937–940. Springer US, Boston, MA.

[2] Christoph Bertram, Gunnar Luderer, Alexander Popp, Jan Christoph Minx, William F. Lamb, Miodrag Stevanović, Florian Humpenöder, Anastasis Giannousakis, and Elmar Kriegler. Targeted policies can compensate most of the increased sustainability risks in 1.5°c mitigation scenarios. *Environmental Research Letters*, 13(6), 2018.

[3] Eric Brousseau, Tom Dedeurwaerdere, Pierre-André Jouvet, and Marc Willinger. Introduction: Global Environmental Commons: Analytical and Political Challenges in Building Governance Mechanisms1. In *Global Environmental Commons*, pages 1–28. Oxford University Press, jul 2012.

[4] Brian Cox, Christopher L Mutel, Christian Bauer, Angelica Mendoza Beltran, and Detlef P. van Vuuren. Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environmental Science & Technology*, 52(8):4989–4995, apr 2018.

[5] Felix Creutzig, N. H. Ravindranath, Göran Berndes, Simon Bolwig, Ryan Bright, Francesco Cherubini, Helena Chum, Esteve Corbera, Mark Delucchi, Andre Faaij, Joseph Fargione, Helmut Haberl, Garvin Heath, Oswaldo Lucon, Richard Plevin, Alexander Popp, Carmenza Robledo-Abad, Steven Rose, Pete Smith, Anders Stromman, Sangwon Suh, and Omar Masera. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, 7(5):916–944, sep 2015.

[6] Oliver Fricko, Simon C Parkinson, Nils Johnson, Manfred Strubegger, Michelle TH van Vliet, and Keywan Riahi. Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, 11(3):034011, mar 2016.

[7] Thomas Gibon, Anders Arvesen, and Edgar G. Hertwich. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, 76:1283–1290, sep 2017.

[8] Thomas Gibon, Edgar G Hertwich, Anders Arvesen, Bhawna Singh, and Francesca Verones. Health benefits, ecological threats of low-carbon electricity. *Environmental Research Letters*, 12(3):034023, mar 2017.

[9] Mark Goedkoop, Reinout Heijungs, An De Schryver, Jaap Struijs, and Rosalie van Zelm. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. page 133, 2009.

[10] Reinout Heijungs and Sangwon Sun. *The computational structure of life cycle assessment*, volume 7 of *Eco-Efficiency in Industry and Science*. Springer Netherlands, Dordrecht, 2002.

[11] Edgar G. Hertwich, Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin A. Heath, Joseph D. Bergesen, Andrea Ramirez, Mabel I. Vega, and

Lei Shi. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences*, 112(20):6277–6282, may 2015.

[12] IPCC. *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 University Press, Cambridge, 2014.

[13] IPCC. Global warming of 1.5°C An IPCC 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, . 2018.

[14] IPCC. Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL). Technical report, 2019.

[15] Timothy M. Lenton, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen, and Hans Joachim Schellnhuber. Climate tipping points - too risky to bet against. *Nature*, 575(7784):592–595, nov 2019.

[16] W.F. Lloyd. Two lectures on the checks to population : delivered before the University of Oxford. sep 1833.

[17] Gunnar Luderer, Michaja Pehl, Anders Arvesen, Thomas Gibon, Benjamin L. Bodirsky, Harmen Sytze de Boer, Oliver Fricko, Mohamad Hejazi, Florian Humpenöder, Gokul Iyer, Silvana Mima, Ioanna Mouratiadou, Robert C. Pietzcker, Alexander Popp, Maarten van den Berg, Detlef van Vuuren, and Edgar G. Hertwich. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, 10(1):5229, dec 2019.

[18] Angelica Mendoza Beltran, Brian Cox, Chris Mutel, Detlef P. Vuuren, David Font Vivanco, Sebastiaan Deetman, Oreane Y. Edelenbosch, Jeroen Guinée, and Arnold Tukker. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, page jiec.12825, nov 2018.

[19] Jan C Minx, William F Lamb, Max W Callaghan, Sabine Fuss, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, Wagner de Oliveira Garcia, Jens Hartmann, Tarun Khanna, Dominic Lenzi, Gunnar Luderer, Gregory F Nemet, Joeri Rogelj, Pete Smith, Jose Luis Vicente Vicente, Jennifer Wilcox, and Maria del Mar Zamora Dominguez. Negative emissions-Part 1: Research landscape and synthesis. *Environmental Research Letters*, 13(6):063001, jun 2018.

[20] I. Mouratiadou, M. Bevione, D. L. Bijl, L. Drouet, M. Hejazi, S. Mima, M. Pehl, and G. Luderer. Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, 147(1-2):91–106, mar 2018.

[21] Michaja Pehl, Anders Arvesen, Florian Humpenöder, Alexander Popp, Edgar G. Hertwich, and Gunnar Luderer. Understanding future emissions from low-carbon

power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, 2(12):939–945, dec 2017.

[22] Alexander Popp, Katherine Calvin, Shinichiro Fujimori, Petr Havlik, Florian Humpenöder, Elke Stehfest, Benjamin Leon Bodirsky, Jan Philipp Dietrich, Jonathan C. Doelmann, Mykola Gusti, Tomoko Hasegawa, Page Kyle, Michael Obersteiner, Andrzej Tabeau, Kiyoshi Takahashi, Hugo Valin, Stephanie Waldhoff, Isabelle Weindl, Marshall Wise, Elmar Kriegler, Hermann Lotze-Campen, Oliver Fricko, Keywan Riahi, and Detlef P. van Vuuren. Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42:331–345, jan 2017.

[23] Celine Ramstein, Goran Dominioni, Sanaz Ettehad, Long Lam, Maurice Quant, Jialiang Zhang, Louis Mark, Sam Nierop, Tom Berg, Paige Leuschner, Cara Merusi, Noernie Klein, and Ian Trim. *State and Trends of Carbon Pricing 2019*. The World Bank, jun 2019.

[24] Shilpa Rao, Zbigniew Klimont, Joana Leitao, Keywan Riahi, Rita Van Dingenen, Lara Aleluia Reis, Katherine Calvin, Frank Dentener, Laurent Drouet, Shinichiro Fujimori, Mathijs Harmsen, Gunnar Luderer, Chris Heyes, Jessica Strefler, Massimo Tavoni, and Detlef P. Van Vuuren. A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, 11(12):124013, dec 2016.

[25] United Nations Environment Programme. *UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi*. 2018.

[26] Toon Vandyck, Kimon Keramidas, Alban Kitous, Joseph V. Spadaro, Rita Van Dingenen, Mike Holland, and Bert Saveyn. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, 9(1):1–11, 2018.

[27] Kathrin Volkart, Nicolas Weidmann, Christian Bauer, and Stefan Hirschberg. Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland. *Energy Policy*, 106:155–168, jul 2017.

[28] Gregor Wernet, Christian Bauer, Bernhard Steubing, Jürgen Reinhard, Emilia Moreno-Ruiz, and Bo Weidema. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9):1218–1230, sep 2016.

[29] J. Jason West, Steven J. Smith, Raquel A. Silva, Vaishali Naik, Yuqiang Zhang, Zachariah Adelman, Meridith M. Fry, Susan Anenberg, Larry W. Horowitz, and Jean Francois Lamarque. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, 3(10):885–889, 2013.

[30] World Bank. Turn down the heat : climate extremes, regional impacts, and the case for resilience. Technical report, 2013.

Chapter 2

Air Quality Co-benefits of Ratcheting-up the NDCs*

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Air Quality Co-benefits of Ratcheting-up the NDCs, Climatic Change (2020) (accepted version)

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Abstract

The current nationally determined contributions, pledged by the countries under the Paris Agreement, are far from limiting climate change to below 2°C temperature increase by the end of the century. The necessary ratcheting up of climate policy is projected to come with a wide array of additional benefits, in particular a reduction of today's 4.5 million annual premature deaths due to poor air quality. This paper therefore addresses the question how climate policy and air pollution related health impacts interplay until 2050 by developing a comprehensive global modelling framework along the cause and effect chain of air pollution-induced social costs. We find that ratcheting up climate policy to a 2°C-compliant pathway results in welfare benefits through reduced air pollution that are larger than mitigation costs, even with avoided climate change damages neglected. The regional analysis demonstrates that the 2°C pathway is therefore, from a social cost perspective, a "no-regret option" in the global aggregate, but particular for China and India due to high air quality benefits, and also for developed regions due to net negative mitigation costs. Energy and resource exporting regions, on the other hand, face higher mitigation cost than benefits. Our analysis further shows that the result of higher health benefits than mitigation costs is robust across various air pollution control scenarios. However, although climate mitigation results in substantial air pollution emission reductions overall, we find significant remaining emissions in the transport and industry sectors even in a 2°C world. We therefore call for further research in how to optimally exploit climate policy and air pollution control, deriving climate change mitigation pathways that maximize co-benefits.

Keywords: air pollution, co-benefits, climate change, health impacts

As acknowledged through the Paris Agreement, climate change will require international collective action to limit the global mean temperature increase to well below 2 °C above pre-industrial levels. Economic costs are one of the main concerns of policy makers, who report their planned climate policies in the form of nationally determined contributions. However, the anticipated decarbonization of the economy, and especially the transformation of the energy system, come with additional benefits and challenges concerning the sustainability dimensions of economy, society and ecology.

In contrast to economic implications, the evaluation of societal and ecological impacts is often less straightforward and can involve sensible ethical questions, for example in regards to the monetary value of ecosystem services or human health as well as the unclear distribution of costs across different societal groups. Nevertheless, the magnitude of the potential co-benefits of climate mitigation - illustrated for example by the 9 million premature deaths attributable to environmental pollution in 2015, as estimated by Landrigan et al. (2018) - should merit them for consideration in climate policy assessments. Local air pollution is exceptionally notable, as it is responsible for about two-thirds of all premature deaths from environmental pollution (Landrigan et al. 2018). It dwarfs in comparison other causes of avoidable deaths more salient in the public eye (such as the 430,000 annual deaths from interpersonal violence and 170,000 from drug use), as well as causes which receive considerable financial support (1.39 million annual deaths from road accidents) (Wang et al. 2016). Our research therefore contributes to the holistic assessment of climate policies by analyzing the interplay of these policies with air pollution related health impacts.

Although air pollution has a multitude of negative impacts on the environment (e.g. acid rain, eutrophication) and the economy (e.g. the decrease of capital value, productivity loss from the workforce, crop yield losses), the most relevant in terms of social cost are effects on human health mainly via cardio-vascular disease, others we are just beginning to understand. They range from reduced cognitive performance (Duncan 2014) to an increase in infant mortality (Heft-Neal et al. 2018) and newly discussed impacts on brain health such as the increased risk of dementia (The Lancet Neurology 2018). In the present study, we focus on the most impactful and well researched health impact, the increased mortality risk due to diseases caused by long-term exposure to concentrations of air pollution.

Analyzing co-benefits of climate change mitigation has received quite some attention from the research community, see Deng et al. (2017) for a general review and Gao et al. (2018) for a public health specific review. Recent literature on the nexus of climate change and air pollution analysed the effects of different climate and air pollution policy scenarios in terms of reduced pollution concentration levels (Rao et al. 2016), estimated the social costs of air pollution to be comparable to the mitigation cost (West et al. 2013, Vandyck et al. (2018)), analysed the health co-benefits under different distributions of climate change abatement efforts (Rafaj et al. 2012, Markandya et al. (2018)), and focused on regional characteristics (Xie et al. 2018, Li et al. (2018)). However, the magnitude of these benefits depend on the development of air pollution controls determining the emission factors of technologies as well as socioeconomic trends determining the potentially affected population size. Our research adds to this discussion by introducing a regionally, sectorally and temporally explicit analysis of the monetized co-benefits relative to the climate policy costs. In contrast to existing literature, we assess different climate policies in combination with air pollution control scenarios with a special focus on the congruent implementation of the spatially explicit socioeconomic features of the scenarios in all of the modelling steps. This is especially important since socioeconomic trends play a crucial role in the development of the Energy-Economy-Climate nexus and for the health impacts of air pollution. Socioeconomic trends not only drive energy demand but also increase the affected population size (population growth, demographic change) and concentrate people in high pollution areas (urbanization). We use a common Shared Socioeconomic Pathways (SSP) (O'Neill et al. 2017) scenario, corresponding to the SSP2 pathway.

1. Methods

Analyzing the interplay of climate policy and air pollution-related health impacts requires a comprehensive modelling framework along the cause and effect chain of air pollution-induced health costs, stylized in Fig. 1. We couple state of the art models from the energy-economy-climate development (REMIND), sector-specific emission factor developments (GAINS), resulting pollutant concentrations through an atmospheric chemistry transport model (TM5-FASST) and spatially explicit socioeconomic trends to estimate the health impacts and their social cost. We apply the framework to the scenario space spanned by climate policy and air pollution legislation.

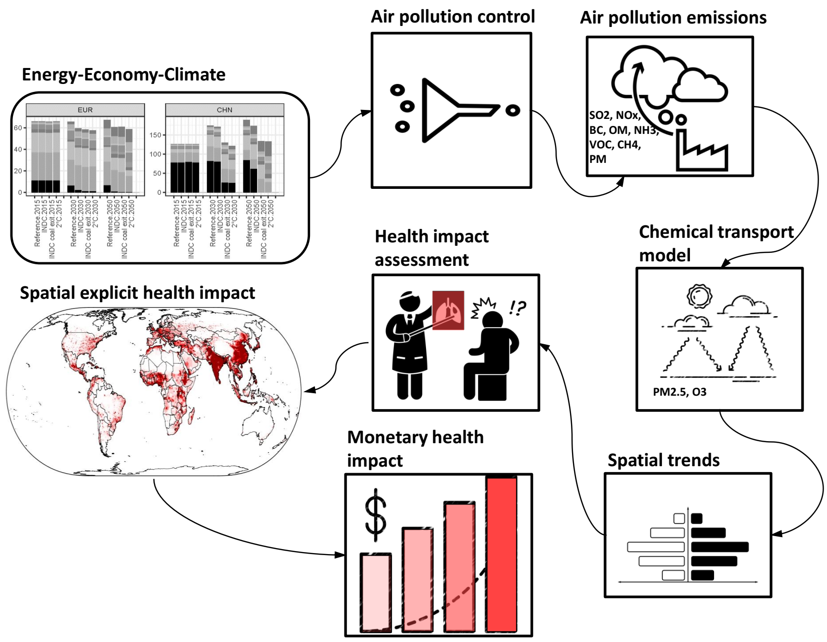
1.1. Energy-Economy-Climate Modeling

The starting point of the model chain is the global energy-economy general equilibrium model REMIND available at https://github.com/remindmodel/remind, linking a macro-economic growth model with a bottom-up energy system model (Bauer et al. 2008, Bauer et al. (2012), Leimbach et al. (2010), Luderer et al. (2016)). This integrated assessment model is built around a Ramsey-type growth macroeconomic core which maximizes inter-temporal welfare, inducing associated energy demands. These are fulfilled through the energy system model by converting primary to secondary and final energy while considering primary energy resources as well as renewable energy potentials. More than 50 conversion technologies are considered, representing system characteristics, costs and their respective development. The model accounts for major drivers of energy system inertia and path dependencies by representing full age specific capacity structure, technological learning, and technology ramping cost. The model is calibrated to a rich data set of historical developments. The implementation of different climate policies in the form of prescribed greenhouse gas (GHG) emission budgets and explicit energy sector policies such as energy-sector fuel taxes and consumer subsidies facilitate the comprehensive assessment of different policy scenarios.

1.2. Air pollution emissions

We model the progression of air pollution control through the change of technology-specific aggregated emission factors over time. These are derived

Figure 1: Modelling framework of the cause effect chain of energy-economy-climate to monetized health impacts of air pollution. (symbols from Thenounproject.com])



from the GAINS model (Amann 2012), encompassing all relevant air pollution species. GAINS projects the air pollution policy goals and their implementation as well as relevant technology research, development, deployment and diffusion (RDD&D). We use these projections to construct three air pollution control scenarios further described in 1.6. These GAINS emission factors are then mapped to REMIND activities on final energy level for industry, buildings and transport, on secondary energy level for electricity, and on primary energy level for fossil fuel production and distribution, see table SI-3. This ensures a comprehensive modeling of sectoral substitution effects. Non-energy related emissions are modeled also through activity specific emission factors where they are included in the REMIND model (industry, agriculture) or taken exogeniously (waste, aviation and international shipping). This is important where climate policy for example leads to higher biomass demand and emissions. Bulk materials related emissions, available in GAINS, are included by scaling with economic output where no specific activity is available in REMIND with an elasticity of 0.4. The regional resolution for the air pollution emission modeling is the REMIND regions (using region specific emission factors), however the emission results are then harmonized to country specific data described in the following section.

Our analysis only considers ambient air pollution. Indoor air pollution is estimated to contribute almost half of all air pollution related premature deaths

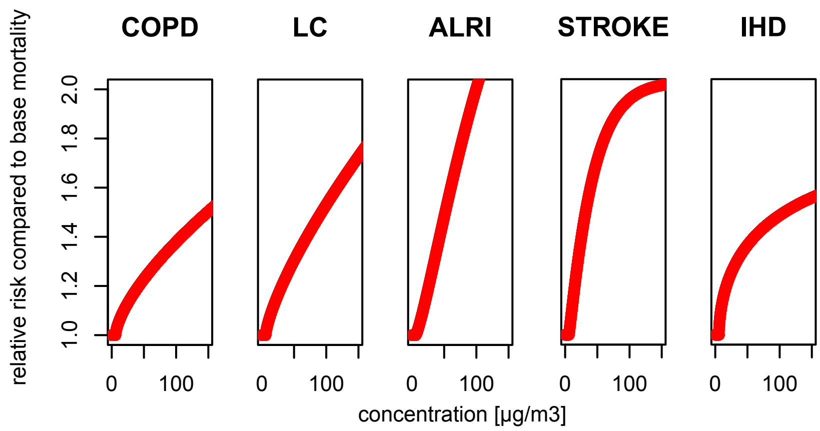
(Landrigan et al. 2018) and is therefore a very important factor particularly in developing countries. However, our modeling does not capture the relevant dynamics of e.g. traditional fireplaces. We therefore focus on ambient air pollution. The costs of emission control technologies and the potential induced efficiency penalty is not considered.

1.3. Atmospheric Chemistry Transport Modeling

Reconciling the regional resolution of REMIND (12 world regions) and the version of GAINS used (24) with the atmospheric chemistry transport model requires a spatial downscaling. We therefore employ a country and sector specific downscaling routine utilizing population and GDP based emission intensities and their development based on the convergence method of Vuuren et al. (2007). In a first step we calculate country specific emission intensities relative to the GDP and population for the base year. The GDP and population development of the modeling years gives a emission intensity growth rate which we then use to calculate the modeling years emission intensity and emissions. The difference of the sum of country and regional emissions is then distributed accordingly to the countries which gives the final country specific emission. These emission results are then harmonized through the aneris model (Gidden et al. 2018) to the sector specific historical emissions of the Community Emissions Data System (CEDS) (Hoesly et al. 2018). In general, the model underestimates 2015 emissions compared CEDS by around 22%, which is explained through an incomplete representation of emission causing activities in the model. Aneris analyses the historic CEDS results, the model results, and relative difference between the two in the base year 2015. It then applies a decision tree to chose which harmonization method to chose specific to emissions, regions and sectors.

We employ the global linearized atmospheric chemistry transport model TM5-FASST (Van Dingenen et al. 2018). It is derived through perturbation runs from the full chemical transport model TM5. The model calculates the concentrations for particulate matter ($PM_{2.5}$) and Ozone (O_3) on a $1° \times 1°$ grid resolution from emission results aggregated to 56 world regions. Included emissions are SO_2, NO_x, black carbon(BC), organic matter(OM), NH3, volatile organic carbon (VOC) and CH4 from anthropogenic emissions as well as natural emission sources (sea salt and dust). These natural sources are very high in some very sparsely populated regions, mostly in the Sahara and the Tibetan Plateau. Besides the regional and sectoral harmonization of emissions, the resulting $PM_{2.5}$ concentrations are harmonized and down-scaled to the Data Integration Model for Air Quality (DIMAQ) developed by Shaddick et al. (2018) with output data available at WHO (2016). The model combines ground measurement and satellite data to estimate mean annual $PM_{2.5}$ concentrations at a high spatial resolution of $0.1° \times 0.1°$. Spatially explicit multiplicative factors for the base year are calculated for every $0.1° \times 0.1°$ of the DIMAQ and $1° \times 1°$ of TM5-FAAST grid. These factors are kept constant and applied to the non-base year modeling period. This downscaling leads to an increase of $PM_{2.5}$ related deaths of 26.5% in the base year 2015 and 32.5% in the 2°C scenario in 2050.

Figure 2: Integrated exposure response functions describing the relationship between annual mean ambient $PM_{2.5}$ and relative risk of the five considered disease endpoints. For adults ($> 30a$), these endpoints are ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD) and lung cancer (LC), and for children under 5, acute respiratory lung infection (ALRI).



1.4. Health impact assessment

The health impact assessment is based on the method laid out in Anenberg et al. (2010) with the updated integrated exposure response (IER) model parameters from Burnett et al. (2014). We consider premature mortality attributable to ambient $PM_{2.5}$ for five major disease endpoints for which particulate matter was considered a risk factor in the Global Burden of Disease study (Cohen et al. 2017); for adults ($> 30a$), these endpoints are ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD) and lung cancer (LC), and for children under 5, acute respiratory lung infection (ALRI). In line with Burnett et al. (2014), the toxicity of $PM_{2.5}$ is assumed to differ only with regard to inhaled mass (exposure) and not with $PM_{2.5}$ composition. O_3 related health impact assessment from respiratory disease follows Jerrett et al. (2009). It is based on the seasonal (April–September) average daily 1-hr maximum concentration.

The relative risk RR, which describes the risk relative to the base mortality rate, for $PM_{2.5}$ concentrations is calculated through the IER functions according to Burnett et al. (2014), the shapes of which are determined by α_d,γ_d and δ_d, the disease endpoints d specific results are shown in Fig. 2:

$$RR_{d,c} = 1 + \alpha_d \left\{exp\left[-\gamma_d(c - c_{cf})^{\delta_d}\right]\right\}$$

The IER functions have a concave shape and drop to one at a concentration c_{cf} of $5.8\mu g/m3$. This theoretical minimal risk is counter intuitive and only a result of a lack of studies with accordingly clean environments. Sensitivity analysis showed that when no theoretical minimal risk is assumed the health impact is on average 21% higher across the scenarios. The attributable fraction a is multiplied by the baseline mortality rate y_0 and exposed population p to obtain the delta of mortality:

$$a_d = \frac{RR_d - 1}{RR_d}$$

$$\Delta m = \sum_{i=1}^{z} y_{0,d}\, a_d\, p$$

New research points in the direction of higher health impacts from air pollution. Stanaway et al. (2018) included the effect of air pollution on Type 2 Diabetes and extended the acute respiratory lung infection assessment for all ages. In combination with recent studies applying a lower theoretical minimum risk concentration Burnett et al. (2018), our co-benefit analysis can be seen as a conservative estimate.

Cause-specific base data from the WHO data (World Health Organization 2012) for 10 world regions is mapped to the spatial grid. This data is available until 2030, we apply a linear extrapolation for the period until 2050. The base mortality data is not varied across the scenarios. The age structure of the population is taken from KC and Lutz (2017), who supply country specific projections. We downscale this data uniformly within each country to our spatial grid.

Socioeconomic trends not only play a critical role in evaluating air pollution related health impacts through their role on the energy system in terms of demand and regional distribution effects, they also materialize in spatial trends of population development. Thus, determining the affected cohort by population growth, demographics, redistribution and migration as well as the clustering in traditionally high pollution areas through urbanization. Recent efforts to develop spatially explicit SSP data, facilitate capturing distributional effects, relevant for air pollution modelling. In this study we use the time changing spatial distributions for population of the "middle-of-the-road" SSP2 scenario from Jones and O'Neill (2016) with a resolution of 1/8°.

1.5. Monetizing the health impacts

In order to relate the health impacts to climate change mitigation costs, they must be translated into a social cost. We employ a willingness-to-pay approach based on a meta-analysis of stated-preference studies by the OECD to estimate the value of a statistical life (VSL) (OECD 2012). VSLs reflect the amount a person is willing to pay to mitigate the mortality risk summed up to one statistical life. Although the stated-preference approach is not based on empirical data and therefore comes with the drawbacks of hypotheticality, it can be applied to a large set of the population and policies in contrast to revealed preference methods, which are often based on analysis of the labor market. However, the lack of consistent studies estimating VSLs for all regions of the world necessitates a method to spatially and temporally transfer the employed VSL from the reference region EU-28. We use the unit value transfer method adjusting with GDP PPP per capita Y and an elasticity ε of 1.2 and 0.8 for countries with a lower and higher income than the reference region in the base year 2005 (3.6 Mio $2005). All regional VSL are in the 'VSL.csv' table in the SI.

$$VSL_{c,t} = VSL_{EU,2005} \frac{Y_{c,t}}{Y_{EU,2005}}^{\varepsilon}$$

Intuitively, the VSL should decline with age (less life years lost) and indeed, there is research pointing to the heterogeneity regarding age (Viscusi 2010). However, there is no comprehensive data on the "senior mortality discount" (Krupnick 2008, Aldy and Viscusi (2007)) as well as the "child mortality premium" (Alberini et al. 2010). We consequently apply an uniform VSL regardless of age.

1.6. Scenario set

We span the scenario space across two dimensions: climate policy and air pollution control, see table 1. For climate policies, we model a Reference scenario, the climate policies as currently pledged under the Nationally Determined Contributions (NDC), as well as strengthened efforts (cost-optimal pathways limiting warming to 2°C mean global temperature rise by the end of the century). The air pollution scenarios only affect the air pollution emission factors and range from a fixed emission factors (AP_FE) over a middle-of-the-road (AP_trend) to an ambitious (AP_stringent) scenario described in details below.

The climate policy scenarios are related to the Energy Modeling Forum (EMF)-30 model comparison project scenario "ClimPolicy" for the 2°C scenario Smith et al. this issue. Here emissions of all GHGs are reduced such that cumulative CO2 emissions until the end of the century lead to limiting global warming below 2°C at 50% probability. The NDC scenario corresponds to the "Slower-Action" EMF-30 scenario which also implements greenhouse gas reductions that replicates near-term developments consistent with the NDCs. The Reference (Ref) scenario functions as a baseline case where climate policy is taken as the continuation of current legislation and diffusion of pollution control (see Smith et al. this issue and Harmsen et al. 2019). The NDC scenario additionally assumes efficient implementation of the nationally determined contributions, the central element of the Paris Agreement. They are only defined until 2030. Afterwards, a middle-of-the road paradigm, in between the extreme cases of comprehensive policy towards the Paris-Agreement long-term targets and backsliding towards the no-policy baseline has been assumed. Specifically, carbon prices after 2030 gradually converge across regions towards a level of 70$/t CO2 in 2100. Share targets like the EU's renewable target or China's Low-Carbon target are assumed to be gradually tightened over time and technology and policy transfer increased. The 2°C scenario achieves a cost-optimal pathways limiting warming to 2°C mean global temperature rise by the end of the century through uniform carbon pricing (see SI-1.1.1.)

Table 1: Scenario set.

climate policy	air pollution
Reference	AP_FE
NDC	AP_trend
2°C	AP_stringent

We explore air pollution control cases ranging from a counter-factual scenario with frozen emission factors on 2015 levels (AP_FE), a middle-of-the-way scenario (AP_trend), to a very optimistic (AP_stringent) scenario (see SI-1.1.2.) building on Riahi et al. (2012) and Rao et al. (2017). The AP_trend scenario was constructed with a world in mind where trends broadly follow their historical patterns. It is determined by an efficient implementation of current near-term policies and a gradual strengthening of goals and technology RDD&D for high and medium income countries (current legislation in 2030 and reaching pessimistic maximal feasible reduction values in 2050) and a delayed progress for low income countries. The AP_stringent legislation can be seen as an ambitious air pollution control scenario, characterized by increasingly strict and well-enforced policies already in the short term (25% reduction additionally to already planned policies) along with a convergence to the technical maximal feasible reduction in the long term for high and middle income countries reaching optimistic maximal feasible reduction values in 2050). Low income countries are catching up relatively quickly to short-term Western European levels through implicit technology and policy transfer (convergence of emission factors to Western European levels by 2030 and 2050). See Fig. SI-15-21 for a visualization of the emission factors for electricity generation from coal. These AP_stringent scenario can be interpreted as an extension of the EMF-30 “BCOC-EndU” scenario since advances in all sectors are assumed.

2. Results

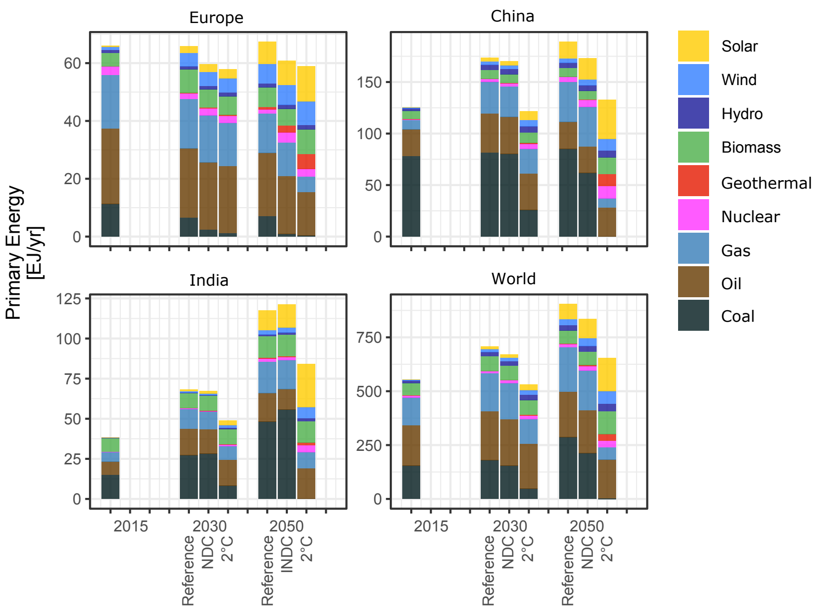
2.1. Energy-Economy-Climate

Fig. 3a shows the primary energy mix of the air pollution AP_trend scenario set for the focus regions Europe, China and India as well as the global aggregate. Corresponding graphs for all world regions as well as for secondary energy and electricity can be found in the Supplementary Material (see Fig. SI-2, 4, 5). As an overall trend, more ambitious climate policy is closely tied to a reduced utilization of fossil fuels (especially coal), the expansion of renewables and the more efficient use of energy.

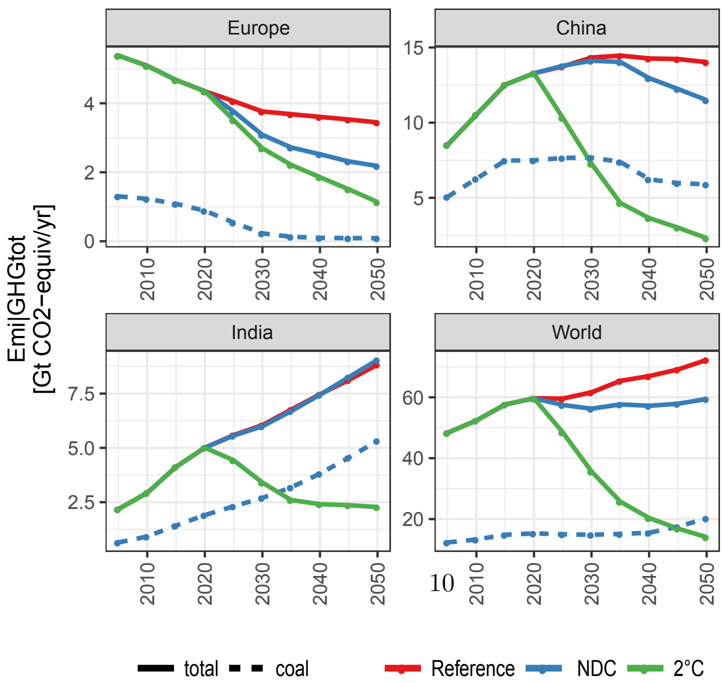
While Europe is phasing out coal already in the short term under the current NDCs, there is only a marginal effect on the primary energy mix of China and India compared to the Reference until 2030. The lack of coal reduction targets in India, in combination with lower demand from other regions, raises the utilization of coal in India relative to reference (the same applies to Sub-Saharan Africa and the Middle East, North Africa, central Asia). The 2°C scenario, in contrast,

Figure 3: Energy-Economy-Climate results of the AP_trend case for the Reference, NDC and 2°C scenario for the focus regions Europe, China, India and the World in 2015, 2030 and 2050. Greenhouse gas emissions include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), F-gases. Each gas is weighted by its global warming potential and aggregated to give total greenhouse gas emissions in CO2 equivalents.

(a) Primary energy supply.



(b) Greenhouse gas emissions- coal related emissions for the NDC in streakline.



necessitates a profound transformation in all regions, not only entailing an accelerated exit from coal but also a considerably higher utilization of renewables and reduction of energy demand (in the long term). The electricity sector plays a crucial role in the 2°C scenario with a quadrupling of demand by 2050, indicating the electrification of other sectors while decarbonizing through a transition to renewables combined with essentially a gas exit (see Supplementary Material Fig. SI-5).

Fig. 2b shows the corresponding greenhouse gas emission trajectories in CO2 equivalents (see the Supplementary Material Fig. SI-3 for all world regions). As expected, more stringent climate policy leads to lower emissions. However, the current NDCs only achieve a stabilization of 2015 levels, resulting in an end-of-century temperature increase of well above 3°C. On the other hand, 2°C-conforming climate policy would significantly reduce GHG emissions until mid-century. The difference between these two scenarios represents the emissions gap identified by United Nations Environment Programme (2018), even assuming efficient implementation of the current NDCs. The need for strengthening the current NDCs in regards to coal is very starkly exemplified in China and India where the coal combustion as allowed by their current NDCs alone would emit more than their total projected emissions in a 2°C scenario from 2030 on.

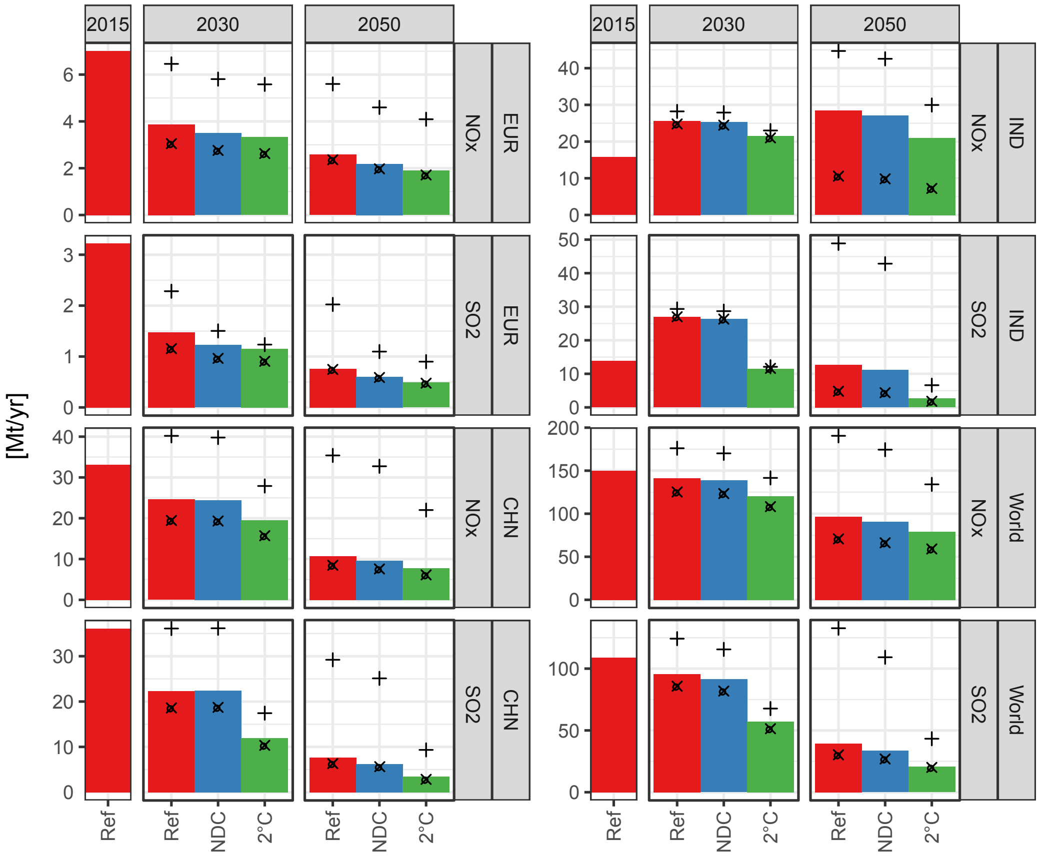
2.2. Emission and concentrations

We focus on $SO2$ and NOx as primary contributors to air pollution for our visualization of the emission results; comprehensive graphs encompassing the sectors Energy, Industry, Residential Commercial, and Transport can be found in the Supplementary Material (see Fig. SI-6-10). We further included the full emission results in the SI data table "emissions.csv". Fig. 4 shows the total emissions, the columns correspond to the AP_trend air pollution control scenario with the AP_stringent and AP_FE marked. The effect of air pollution policy and RDD&D is clearly visible; decreasing emission factors due to air pollution control result in emission reductions in the Ref scenario, despite higher consumption of combustible energy carriers. This suggests that the benefits of climate policy as it relates to air pollution reductions mostly occur before 2050.

A closer look into the effect of climate policy gives two prominent insights: 1) The current NDCs only have a marginal effect on emission levels compared to the Reference. In contrast, the 2°C scenario is able to significantly lower emissions, especially the $SO2$ emissions associated with the combustion of coal. 2) The remaining relatively high NOx emissions in a 2°C world are mainly due to residual emissions from industry and transport (see Supplementary Material Fig. SI-8, 10). Both see rising electrification but only stagnating use of liquide fuels. This highlights that though decarbonizing the energy supply is crucial, the transport and industry sectors hold additional potential for air pollution emission reduction. This is especially relevant due to the concentrated nature of transport emissions such that they are in close proximity to humans in an increasingly urbanized world.

In the regional analysis, we focus on Europe, China and India as examples of mature and emerging economies. Detailed results for other regions are available

Figure 4: Total emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for the focus regions Europe, China, India and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases.



in the Supplementary Material Fig. SI-6.

Europe, representing a developed region, experiences a drop in emission levels already in the Reference scenario due to a reduction of coal and decreasing emission factors, and only comparatively small additional reductions in the climate policy cases. China shows a similar pattern, with a more pronounced reduction in the 2°C scenario compared to the Ref and NDC scenarios. However, recent literature has shown that China experiences a steep decrease of $SO2$ emissions Li et al. (2017) through stricter air pollution control. These recent developments are not included in our emission factor data. The $SO2$ results for China should therefore be seen as counterfactually high estimates. India on the other hand faced rising emissions recently and continuous to do so until 2030 in the Ref and NDC scenarios, and only the ambitious climate policy scenario is able to stabilize or reduce the emission levels until 2050.

All other pollutant emissions can be found in the SI emission table and the figures SI-11-21. All species show a similar, trend as $SO2$ and NOx. However, the emissions from Grassland Burning increase in the ambitious climate policy scenarios compared to the reference case. These emissions are directly liked in the model to higher biomass use.

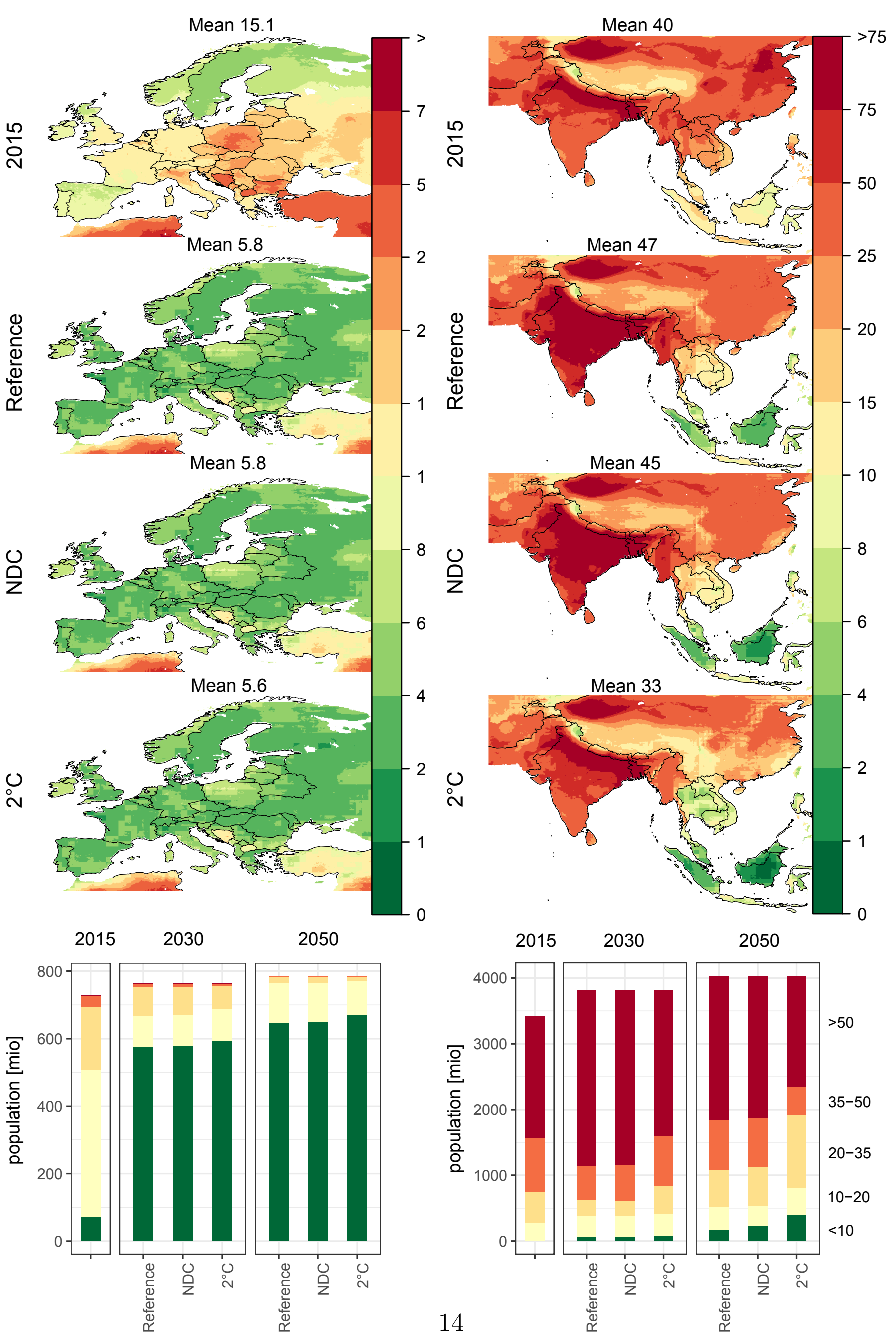
As mentioned above, the AP_stringent scenario can be seen as an ambitious air pollution control world. Contrasting to the AP_trend scenario, it indicates how robust the differences between the climate policy scenarios are. On a global level, AP_stringent air pollution control can achieve lower emission levels in general, especially mid-century; however, the spread between the NDC and 2°C scenarios under stringent pollution controls is similar to the spread under the AP_trend cases. See Fig. 4 the difference of the different climate policy scenarios between the bars and the difference between the ⊗. This supports the argument that synergies of ambitious climate policy are still relevant even under optimistic air pollution control. The AP_FE scenario (+) assumes frozen emission factors on 2015 levels and thus isolates the maximal effect of climate policy on air pollutant emissions. It becomes clear that the air quality benefits of the Ref and NDC are much more sensitive to slow progress in air pollution control than the 2°C scenario, especially in the short term. In conclusion, climate policy is a hedge against slower air pollution control and tighter air pollution control is a hedge against human health impacts from air pollution of slower climate policy progress.

Fig. 5 shows the atmospheric chemistry transport model results for $PM_{2.5}$ concentrations. Plotted there are the base year and the reference and climate policy scenario results of the year 2050 for the AP_trend air pollution control case. We focused primarily on Europe and Southeast Asia (including China and India); however, results were computed for all land areas, shown in the Supplementary Material (Fig. SI-24-26).

The bar chart shows the population fraction exposed to the National Ambient Air Quality Standard of China GB3095-2012 of 35 $\mu g/m3$ (orange), the EU limit of 20 $\mu g/m3$ introduced through the directive 2008/50/EC (yellow) and the WHO guideline of <10 $\mu g/m3$ (green). The EU threshold was exceeded in most of eastern Europe in 2015, especially in Poland and the Balkans but

Figure 5: Mean annual $PM_{2.5}$ concentration [$\mu g/m^3$] for the year 2015 and 2050 under the NDC and 2°C scenarios with the AP_trend air pollution control case for Europe and Southeast Asia. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange), 35>x>20 $\mu g/m3$ (light orange), 20>x>10 $\mu g/m3$ (yellow) and <10 $\mu g/m3$ (green)

(a) Europe (b) Southeast Asia



also parts of Germany and northern Italy. Only Scandinavia and the Iberian Peninsula had already achieved the WHO guideline. Southeast Asia's starting concentration levels are much higher, with the majority of the population living above the Chinese standard, and pollution hot spots were mainly located in Northern India and Eastern China.

In all scenarios modeled, Europe experiences a decrease of concentrations quite analogous to the emission levels. The population exposed to levels above the 20 $\mu g/m3$ limit declines from 79% (400 mio) to 19% (100 mio) already in 2030. In 2050 most of the population is projected to be living under the WHO limit. China also achieves a considerable reduction, especially in the currently highly polluted coastal areas, in the 2°C scenario. India, on the other hand, struggles to reduce concentrations and sees only a slight decrease in the NDC compared to the Reference scenario. The rising concentrations in the Reference and NDC scenario compared to 2015 levels correspond to the steep rise in economic activity, associated energy demand and slow progress in air pollution control. Factoring in population growth and urbanization trends, current NDCs would actually lead to an increase from 86% (2.6 billion) to 89% (3 billion) living in highly polluted areas (>35 $\mu g/m3$) in Southeast Asia in 2050. The 2°C scenario, however, is able to slash concentrations to below the Chinese standard for almost half of the Southeast Asian (including China and India) population.

2.3. Health impacts and cost

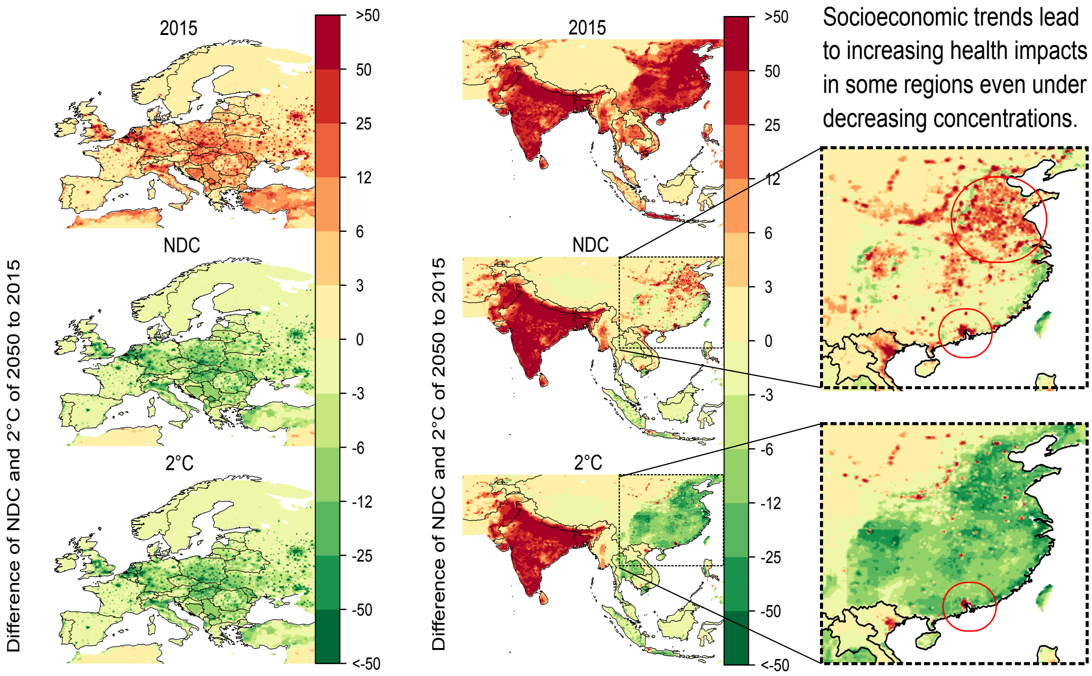
Fig. 6 depicts spatially explicit health impacts in terms of annual premature deaths caused by $PM_{2.5}$ and O_3 concentrations of the AP_trend scenario. Across all scenarios the mortality share of $PM_{2.5}/O_3$ decreases from 92% in 2015 to 80% in 2030 and to around 70% in 2050. The base year is plotted in the top map, and the following rows show the differential of each scenario to the base year. The results for all other regions are in the Supplementary Material (Fig. SI-13-15)

The Reference scenario only has a reduction effect in Europe where stricter air pollution control and some switch from fossils to renewables is occurring without additional climate policies. The 2°C scenario avoids an aggregated premature death toll of 1.1 million people in 2050 alone compared to the Reference case. The current NDCs, on the other hand, only yield a benefit of 130,000 avoided premature deaths.

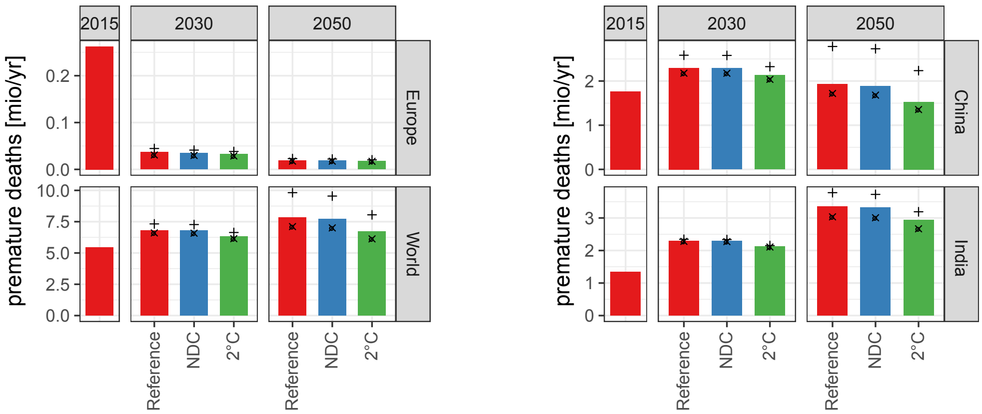
The 2015 air pollution-related mortality in China of more than 1.7 million deaths (80 per 100k inhabitants) highlights the urgency of air pollution reductions; however, the modeling shows that it is a major challenge to reduce the health impact despite lower air pollution concentrations. In fact, the health impact is rising in 2030 in all scenarios and only the 2°C scenario is able to lower the impact in 2050, with the exemption of few high population areas seeing rising premature deaths even under ambitious climate policy due to socioeconomic effects, highlighted in the magnified maps. India is confronted with a similarly severe air pollution crisis, facing 1.3 (99 per 100k inhabitants) million premature deaths in 2015. This number is more than doubled in the Reference scenario until 2050 with minor mitigation effects of the current NDCs. Thus, it becomes

Figure 6: Health impact of $PM_{2.5}$ and O_3 for Europe and Southeast Asia for the year 2015 and relative to 2015 for the year 2050 under the NDC and 2°C scenarios with the AP_trend air pollution control case. Zoomed into areas where socioeconomic trends lead to increasing health impacts even under decreasing concentrations.

(a) Spatially explicit health impact in terms of annual premature deaths in $cases/km^2$.



(b) Bars represent premature deaths for the AP_trend air pollution control scenario, markers represent values in the AP_stringent (⊗) and AP_FE (+) sensitivity cases in million cases per year.



apparent that India is facing major challenges due to socioeconomic trends even in a 2°C scenario, which is reducing the deaths by 500,000 (28 per 100k inhabitants) annually in 2050. (India sees a doubling of the population over 30 years until 2050 and an increase in urbanization from 30 to 53%.)

The AP_stringent and AP_FE scenarios show the magnitude of health impact under ambitious or non-progressing air pollution policy. They significantly affect the health impact with up to 10 million premature deaths globally in the AP_FE Reference scenario, of which most of the burden is on China. This highlights that the air pollution control is assumed to be developing quite rapidly in China in the AP_trend case. Despite shifting the results, fig. 6 shows that the differential between the Ref and 2°C scenario does not change significantly under AP_stringent air pollution control in China, India and globally. This again supports the argument that synergies of ambitious climate policy are still relevant even under optimistic air pollution control.

Figure 7: Climate change mitigation costs (yellow), monetized avoided health damages (red) and net social costs for the AP_trend (●), AP_stringent (⊗) and AP_FE (+) cases. Amounts are cumulated over 2015-2050, discounted at 5% and expressed relative to cumulated and discounted GDP PPP.

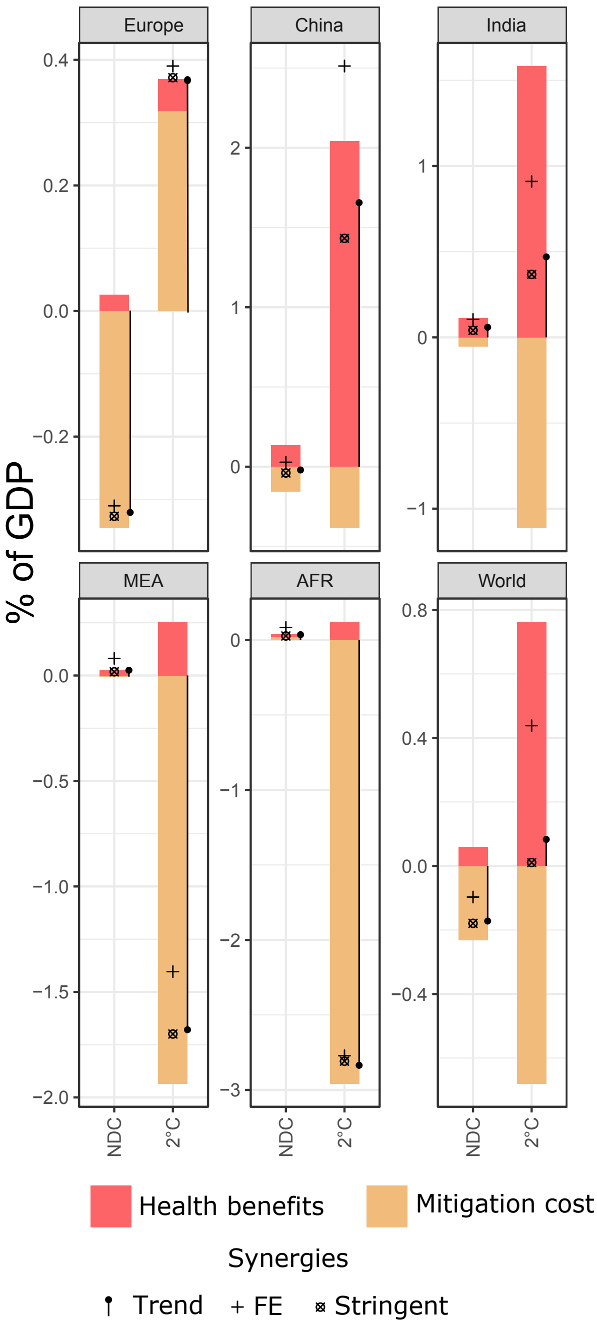


Fig. 7 shows the discounted (5%) climate change mitigation costs (as consumption losses relative to the Reference adjusted for changes in current accounts as described in Aboumahboub et al. (2014)), air quality benefits (as social cost) and resulting net synergies until 2050 as a differential to the Reference case. Althought these are not the same type of cost, we compare them to illustrate the magnitude of air pollution related co-benefits. We extend the analysis here with Middle East, North Africa, central Asia (MEA) as a representative of energy exporting regions and Sub-Saharan Africa (excl. South Africa) as a developing region. The cost calculation for all world regions can be found in the Supplementary Material (Fig. SI-16). Importantly, the analysis only considers the costs of climate change mitigation, but does not account for avoided climate damages.

From a global social cost perspective, we robustly find a net positive effects from 2°C conforming climate policies across air pollution scenarios with a global benefit equal to 0.08% of GDP until 2050 (in line with Vandyck et al. (2018)). In other words, the higher mitigation costs of strengthening the current NDCs to a 2°C compatible climate policy are more than compensated by the associated lower health impacts. Especially the emerging countries China and India see a illustrative net benefit of equal to 1.5% and 0.5% of GDP (in line with regional literature Li et al. (2018)). The current NDCs on the other hand come with much less air pollution benefits which, in combination with still significant mitigation cost, results in a global net negative effect equal to -0.18% of GDP (almost cost neutral for China and +0.1% for India).

However, the regional analysis presents a more diverse picture. Europe, as a developed region, already reduces air pollution in the Reference case through ambitious air pollution legislation, which results in low additional benefits of the climate policy scenarios. Nevertheless, the 2°C scenario yields the highest illustrative net benefits due to negative mitigation cost. Here a combined effect of reduced prices for fossil fuels result in lower variable and fixed energy system cost. In combination with only small consumption losses from GDP effects compared to the developing countries, results in negative mitigation cost (see fig. SI-1 for a decomposition of mitigation cost in 2030). China and India, as hot-spots of air pollution, on the other hand, strongly benefit from climate policy induced improvements in air quality compared to the mitigation cost. The situation is flipped in fossil fuel exporting regions such as MEA, here the 2°C scenario inflicts high mitigation costs with limited air pollution benefits. Sub-Saharan Africa, as a developing region, is confronted with relatively high mitigation cost because of the high carbon intensity of economic output in combination with limited air quality co-benefits.

The AP_FE and AP_stringent scenarios can be interpreted as sensitivities of the co-benefits of climate policies to the progression of air pollution policies. We find that slower air pollution control, represented by the AP_FE scenario, strongly increase the air pollution benefits and leads to even higher illustrative net benefits than the AP_trend scenario. On a global level, the AP_stringent air pollution control scenario lowers the illustrative net benefits compared to the AP_trend, but they are still positive.

3. Discussion

Climate change and air pollution are both pressing and interconnected issues on a global scale with different regional manifestations. The purpose of this study was to assess the synergies from climate change mitigation policies on reduced health impacts of air pollution under different air pollution control scenarios. We analysed the current NDCs and a 2°C consistent climate policy scenario, focusing on the coherent translation of assumptions and data in all modelling steps such as socioeconomic trends, crucial for the health impact of air pollution. The goal was to quantify the air pollution health impacts and relate them to climate mitigation cost.

In line with United Nations Environment Programme (2018), we find the current NDCs to clearly fall short of achieving a decarbonization suitable to limit climate change to the goals of the Paris Agreement. The NDCs consequently also do not lead to substantial air pollution concentration reduction in China and India compared to the Reference, or in Europe where air pollution policies lower concentrations already in the Reference scenario.

Increasing the stringency of climate policy to a 2°C-conforming pathway significantly raises the mitigation costs compared to the NDCs on a global level; however, these costs are compensated by the air quality health benefits. Or to put it differently, the illustrative net social benefit of weak action, as reflected by the NDC scenario, is lower than the illustrative net social benefit of 2°C-conforming action, already with a narrow focus on air pollution and not even considering the monetary damages from climate change impacts. This holds as a global aggregate but is especially relevant for China and India which benefit from strengthening their NDCs with an aggregated illustrative net benefit equal to 1.5 % and 0.5% of GDP until 2050. Developed regions (Europe, USA and Japan) on the other hand have comparatively low additional air pollution benefits from ratcheting up their NDCs to 2°C conforming mitigation. Nevertheless, the negative mitigation costs in the 2°C scenario result in illustrative net benefits also for these regions, only fossil fuels exporting regions face high mitigation costs and low air pollution benefits.

The assessment of different air pollution control scenarios shows the illustrative net benefits to be potentially much higher if non-effective enforcement of control policies and slower technological progress is assumed, making climate policy a hedge against slow air pollution control. Current developments, for example concerning the road transport sector, suggest the relevance of both such non-effective enforcement and slow progress (Anenberg et al. 2017). Under the assumption of faster and more ambitious adoption of advanced air pollution control, the synergies are lower but still positive for a 2°C scenario. However, it is important to note that lower co-benefits do not mean stringent air pollution control should not be implemented. Our results show considerable remaining health impacts in the AP_trend and even AP_stringent scenario, therefore all measures should be taken to enhance air quality.

We further find that while the 2°C conforming transformation of the energy supply sector substantially reduces air pollution, socioeconomic and spatial trends pose a major challenge to countries with dramatic increases in population, urbanization and GDP, such as India and parts of China. This, in combination with our finding of only slowly decreasing air pollutant emissions compared to 2015 levels in sectors such as transport and industry, emphasizes the need for further research that extends the current ex-post assessment of climate policy scenarios to a dynamic approach. This would allow analyzing how to optimally exploit climate policy and air pollution control sector, region and time specific, deriving transformation pathways that maximize co-benefits.

4. Acknowledgements

The research leading to these results was supported by the INTEGRATE and ENavi projects funded by the German Federal Ministry of Education and Research (BMBF) and by the European Union's Horizon 2020 research and innovation program under grant agreement No 730403 (INNOPATHS).

SI-1 Supplementary Information

SI-1.1. Methodology

SI-1.1.1. Energy-Economy-Climate Modeling

The starting point of the model chain is the IAM REMIND (Bauer et al. 2008, Bauer et al. (2012), Leimbach et al. (2010), Luderer et al. (2016)) available at https://github.com/remindmodel/remind, which provides insights in future GHG emission pathways and options for mitigation, described in this section. An important output of IAMs are GHG pathways representing currently implemented climate policies. The NDC Scenario in REMIND includes currently implemented policies and targets and additionally (after the ratification of the Paris Agreement) the pledges from the NDC. Two main databases are used to construct the NDC scenario: From the REN21 database, we use the "Renewable Power Targets for Specific Amount of Installed Capacity or Generation" (only at a country level) and from Rogelj et al. (2017), we use capacity and generation targets, absolute emission targets, and emission intensity targets ("CO2/GDP", "GHG/GDP", and "GHG/CAP"). Taking into account other parameters, e.g., conditionality of the target, reference/base year and target year etc., we aggregate these targets at a regional level. Capacity and generation targets for specific technologies, expressed as a certain variable in the model, are implemented as considered lower-bound whereas emission and emission intensity targets (also lower bound) are reached through an iteratively adjusted, regionally differentiated carbon tax.

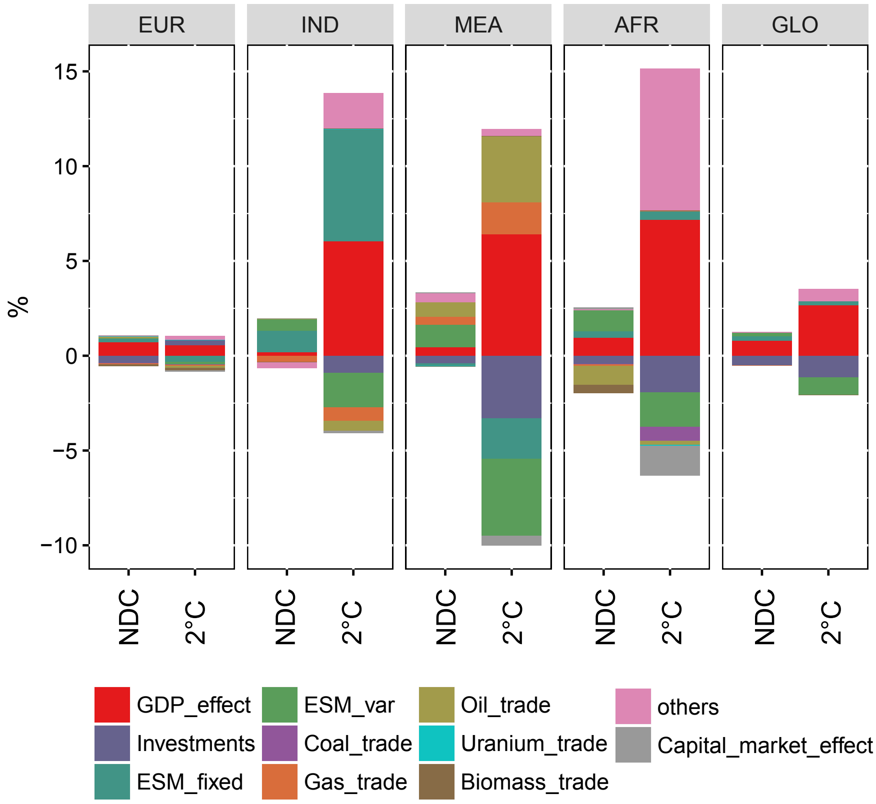
Furthermore, policies and targets outside these databases, important for emission reductions are also considered. However, their spatial dimension is limited to countries which are also regions in the model (e.g., Japan, India, China, USA, EU etc.). The additional polices include but are not limited to: targets for electro-mobility shares of electro-mobility to represent effect of demand-side transport efficiency policies, share of renewables in secondary or final energy, renewable targets as share of total capacity, share of low-carbon sources in secondary energy/electricity. The source of these policies are various government reports and are updated as the policy landscape changes in the country.

As policies and targets, both currently implemented and those explicitly mentioned in the NDC, are only available until 2030/2035, assumptions have to be made to project the emissions pathways beyond this period. This is done by choosing a "middle-of-the road" pathway, i.e., in between the extreme cases of a stringent climate policy compatible with the Paris Agreement (implemented through a carbon budget constraint) and returning to a "no-policy" baseline scenario. Carbon prices after 2030 gradually converge across regions towards a level of 70\$/t CO2 in 2100. Also, share targets like the EU's renewable target or China's Low-Carbon target are assumed to be gradually tightened over time.

The 2°C scenario limits the global mean temperature rise by the end of the century to 2°C through cost effective uniform carbon pricing across regions and sectors.

The decomposition of mitigation cost of the climate policy scenarios relative to the reference scenario for the year 2030 is shown in Fig. SI-1. The cost of air pollution legislation are not considered. On a global level the mitigation cost are dominated by a lower GDP and higher investment cost for the energy system in the climate policy scenarios than the reference scenario. Benefits are mainly cost savings from less expenses on fuel and operation and management cost of the energy system as well as lower non-energy investments. The regionally different magnitudes of mitigation cost reflects the global uniform carbon pricing which incentivises more efforts in developing than developed regions. Additionally, developed regions do not grow as rapidly as developing regions. As a result Europe as a representative of a developed region faces slight mitigation benefits (negative mitigation cost). India on the other hand faces a GDP loss of more than 5% in the 2°C scenario plus similar cost for energy system investments. MEA mainly faces cost associated with less exports of oil and gas and AFR other cost associated with the land-use sector and adjustment cost for investments.

Figure SI-1: Mitigation cost decomposition for the 2°C scenario compared to the Reference scenario relative to GDP for EUR (Europe), IND (India), MEA (Middle East, North Africa, central Asia), Africa (Sub-Saharan Africa (excl. Republic of South Africa)) and the World in 2030. See table SI-1 for a description of the terminology.



SI-1.1.2. Air pollution emissions

The air pollution emission modeling is based on the GAINS model and the work of Rao et al. (2017). We use the 'current legislation' and 'maximum feasible reduction' data set and construct air pollution policy scenarios. The current legislation data set [CLE] assumes efficient implementation of existing environmental legislation. The maximum feasible reduction [MFR] data set assumes full penetration of best available air pollution control technologies in 2015 by 2030.

We assign countries according to their GDP/capita in high [h] and low [l]

Table SI-1: Mitigation cost decomposition terminology.

GDP_effect	GDP loss or gain induced by the climate policy scenario compared to the reference scenario.
Investments	Marco-economic investment cost for non energy related infrastructure.
ESM_fixed	Energy system related investment cost.
ESM_var	Energy system related variable cost. Cost for fuel and operation and management.
Coal_trade	Cost saving through lower import and/or higher export of coal. Higher cost through lower exports and/or higher imports of coal.
Gas_trade	Cost saving through lower import and/or higher export of gas. Higher cost through lower exports and/or higher imports of gas.
Oil_trade	Cost saving through lower import and/or higher export of oil Higher cost through lower exports and/or higher imports of oil.
Uranium_trade	Cost saving through lower import and/or higher export of uran. Higher cost through lower exports and/or higher imports of uran.
Biomass_trade	Cost saving through lower import and/or higher export of biomass. Higher cost through lower exports and/or higher imports of biomass.
Capital_market_effect	Higher or lower cost for capital.
others	Other cost effects such as higher/lower cost from the land-use sector.

Table SI-2: Air pollution policy timeline.

policy scenario	country category	2030	2050
AP_trend	low	[2020, "CLE"]	[2030, "CLE"]
AP_trend	high	[2030,"CLE"]	[2030,"CLE"]
AP_trend	highstrong	[2030,"CLE"]	[2030,"CLE"]- ([2030,"CLE"]-[2030,"MFR"])*0.75
AP_stringent	low	[2030, "CLE"]	[Western Europe ,2030, "CLE"]
AP_stringent	high	[2030,"CLE"]*0.75	[2030,"CLE"]- ([2030,"CLE"]-[2030,"MFR"])*0.75
AP_stringent	highstrong	[2030,"CLE"]*0.75	[2030,"CLE"]- ([2030,"CLE"]-[2030,"MFR"])*0.75
AP_FE	low	[2015,"CLE"]	[2015,"CLE"]
AP_FE	high	[2015,"CLE"]	[2015,"CLE"]
AP_FE	highstrong	[2015,"CLE"]	[2015,"CLE"]

income countries with 2750 US$(2010) as a threshold. We further divide the high income countries in countries with strong pollution policies in place (Western Europe, Japan, Australia, Canada, USA) and countries with lower emissions goals (rest), see data table "country_category.csv" in the SI. Analogous to Rao et al. (2017), we now construct country specific timelines steps of 2030 and 2050 and interpolate between them for the other time steps.

Table SI-3: GAINS REMIND sectoral mapping.

GAINS	REMIND
End_Use_Industry_Bio_Trad	FE|Industry|Solids|Biomass|Traditional
End_Use_Industry_Coal	FE|Industry|Solids|Coal
End_Use_Industry_heavy_liquide_fuel	FE|Industry|Liquids
End_Use_Industry_light_liquide_fuel	FE|Industry|Liquids
End_Use_Industry_NatGas	FE|Industry|Gases
End_Use_Residential_Bio_Mod	FE|Solids|Biomass|Modern
End_Use_Residential_Bio_Trad	FE|Solids|Biomass|Traditional
End_Use_Residential_Coal	FE|Solids|Coal
End_Use_Residential_heavy_liquide_fuel	FE|Buildings|Liquids
End_Use_Residential_light_liquide_fuel	FE|Buildings|Liquids
End_Use_Residential_NatGas	FE|Buildings|Gases
End_Use_Services_Bio_Trad	FE|Solids|Biomass|Traditional
End_Use_Services_Coal	FE|Solids without BioTrad
End_Use_Transport_heavy_liquide_fuel	FE|Transport|Liquids
End_Use_Transport_light_liquide_fuel	FE|Transport|Liquids
End_Use_Transport_NatGas	FE|Transport|Liquids
Losses_Coal	PE|Coal
Losses_Distribution_Use	PE|Oil
Losses_Vent_Flare	PE|Gas
Power_Gen_Bio_Trad	SE|Electricity|Coal
Power_Gen_Coal	SE|Electricity|Coal
Power_Gen_heavy_liquide_fuel	SE|Electricity|Oil
Power_Gen_light_liquide_fuel	SE|Electricity|Oil
Power_Gen_NatGas	SE|Electricity|Gas
Transformations_Coal	SE|Solids|Coal
Transformations_heavy_liquide_fuel	PE|Oil
Transformations_heavy_liquide_fuel_Refinery	PE|Oil
Transformations_light_liquide_fuel	PE|Oil
Transformations_NatGas	PE|Gas
CEMENT	GDP
CHEM	GDP
CHEMBULK	GDP
CUSM	GDP
NACID	GDP
PAPER	GDP
STEEL	GDP

SI-1.2. Results

SI-1.2.1. Energy-Economy-Climate Modeling

Figure SI-2: Primary energy of the AP_trend case for the Reference, NDC and 2°C scenario for JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

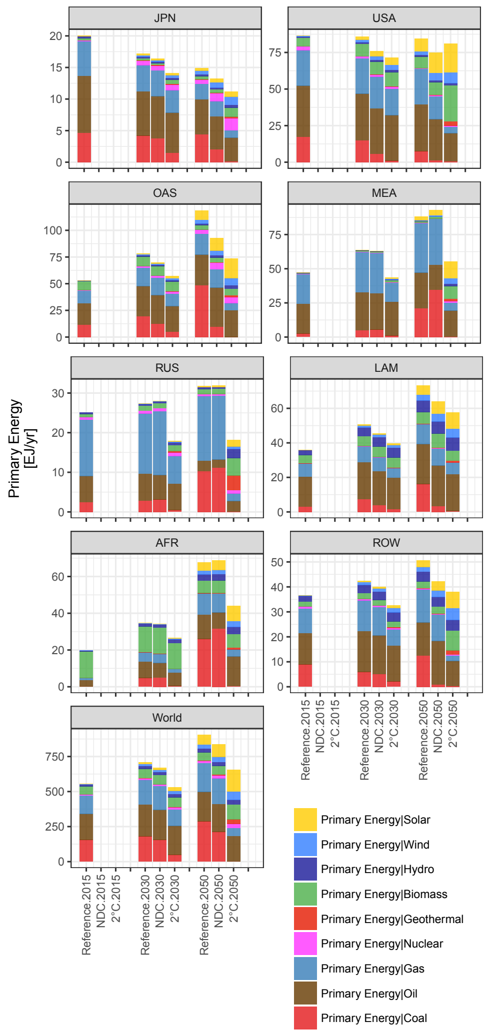


Figure SI-3: Greenhouse gas emissions (carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), F-gases. Each gas is weighted by its global warming potential and aggregated to give total greenhouse gas emissions in CO2 equivalents) (coal related emissions for the NDC in streakline) of the AP_trend case for the Reference, NDC and 2°C scenario for JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Emissions are equal across the air pollution control cases.

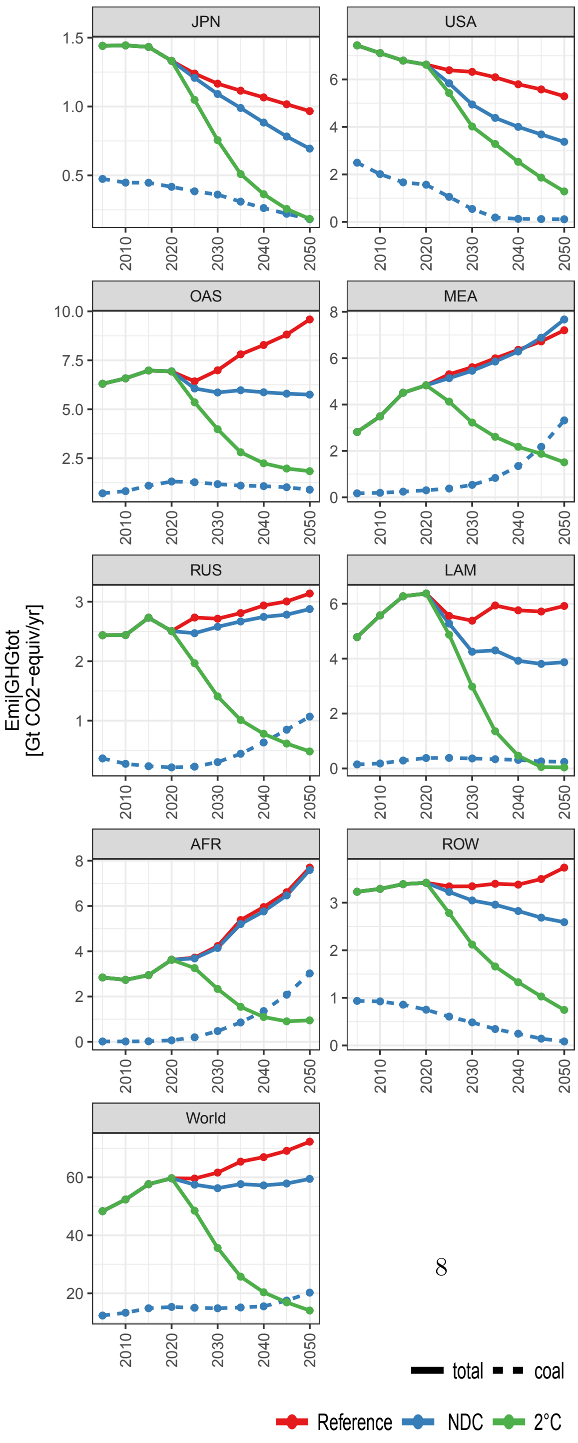


Figure SI-4: Secondary energy of the AP_trend case for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

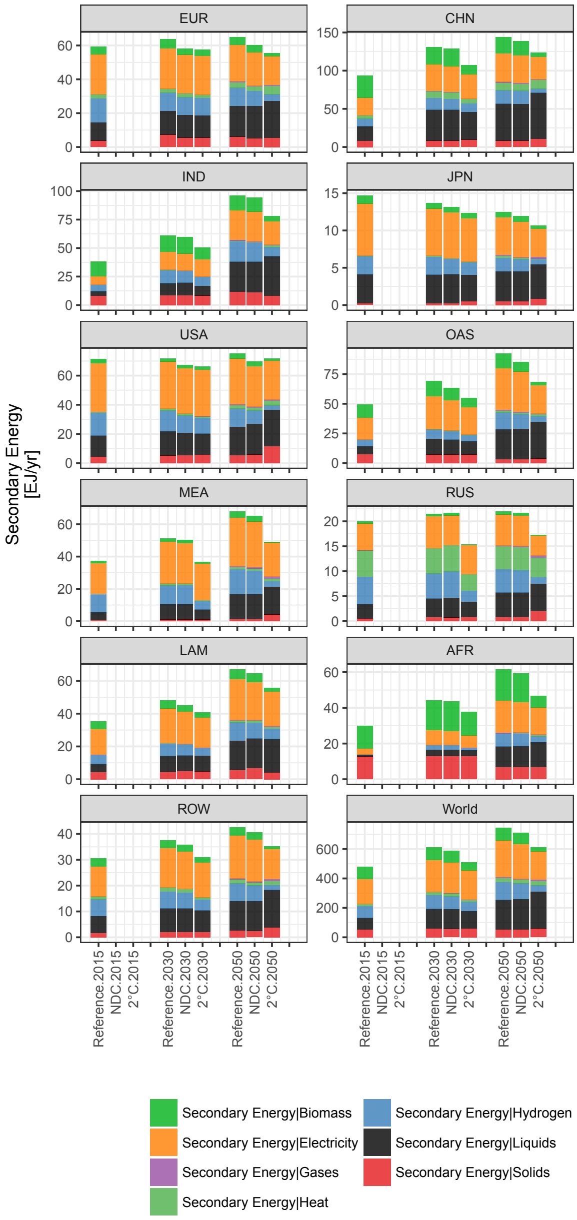
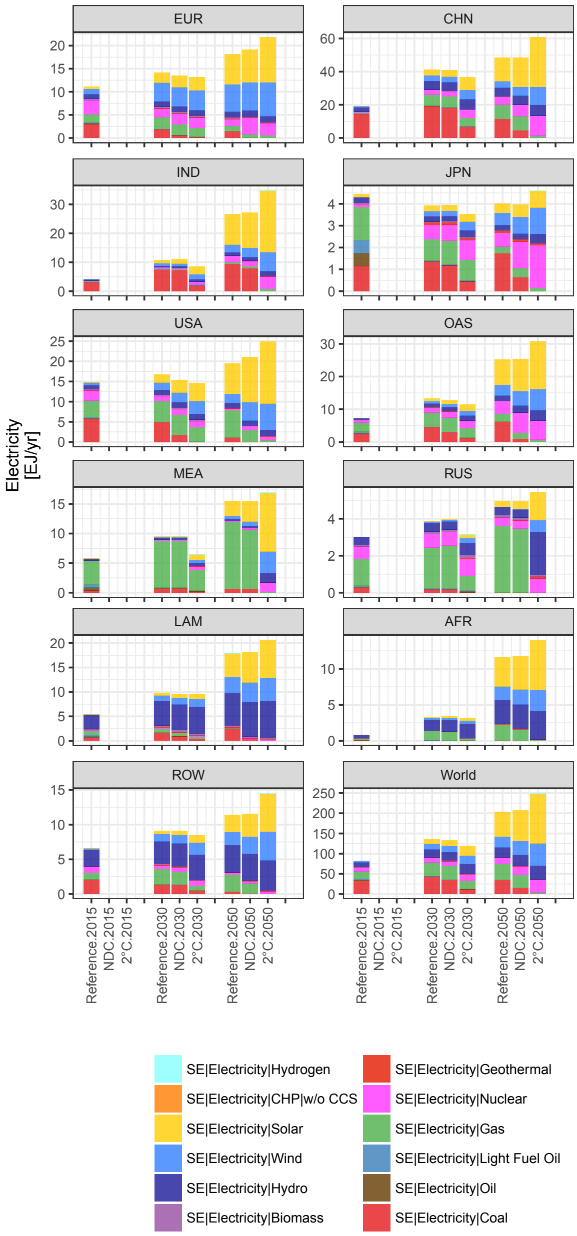


Figure SI-5: Secondary Energy - Electricity of the AP_trend case for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.



SI-1.2.2. Air pollution emissions

Figure SI-6: Total emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases. The energy supply sector share is overlaid in grey.

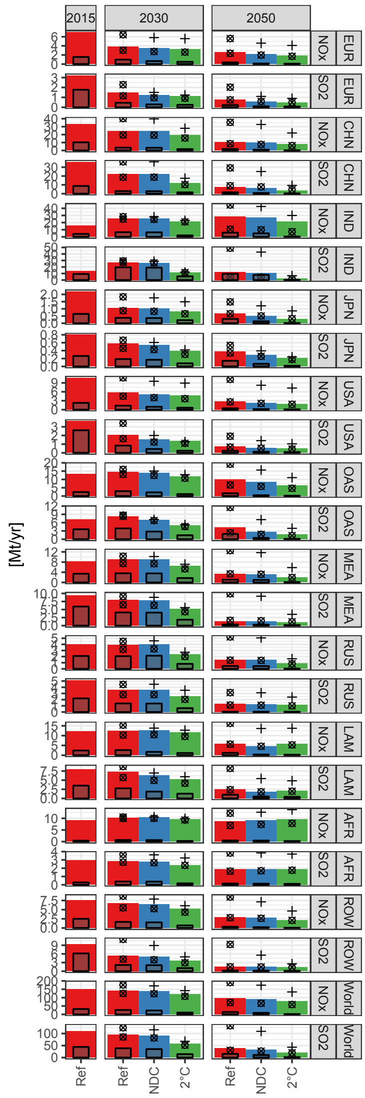


Figure SI-7: Energy supply emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases.

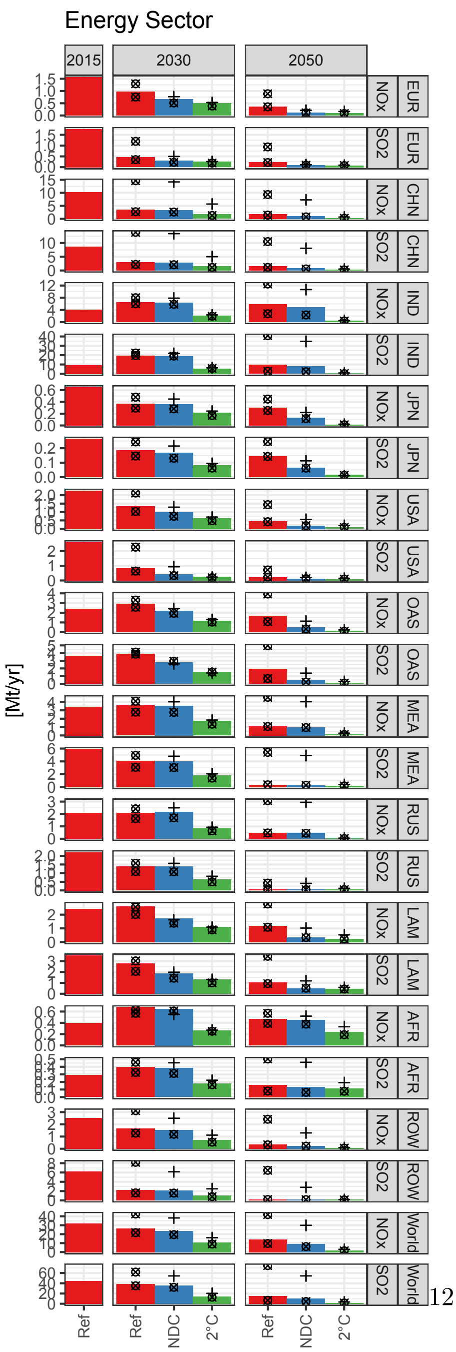


Figure SI-8: Industry emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases.

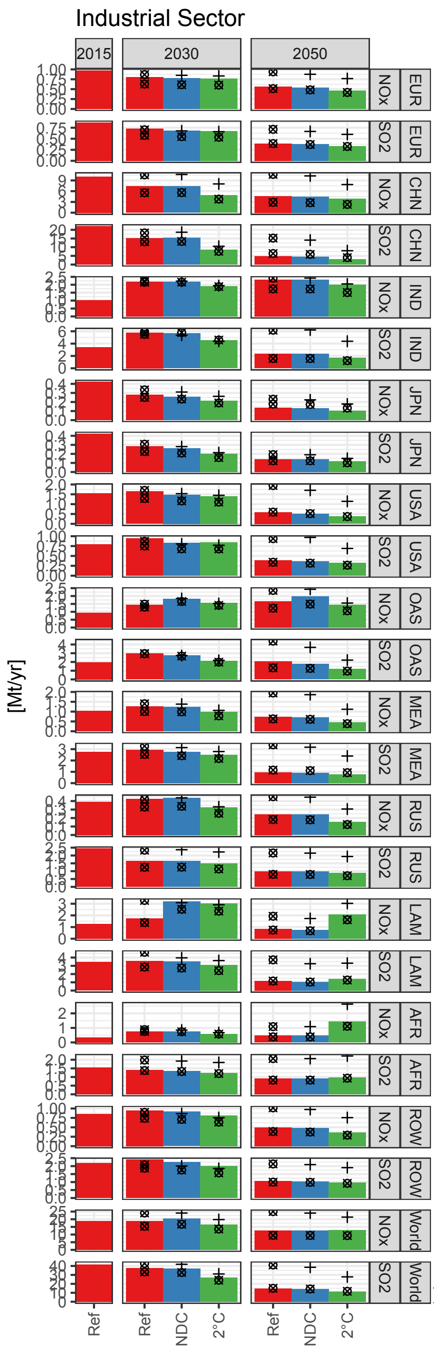


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Figure SI-9: Residental Commercial emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases.

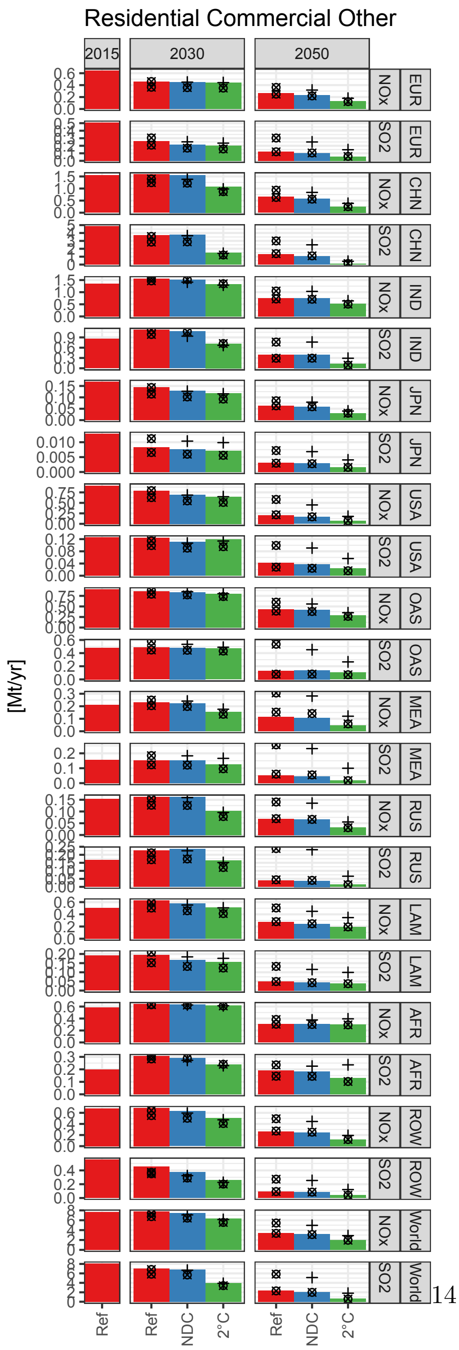


Figure SI-10: Transportation emissions of the air pollutant $SO2$ and NOx for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent (⊗) and AP_FE (+) sensitivity cases.

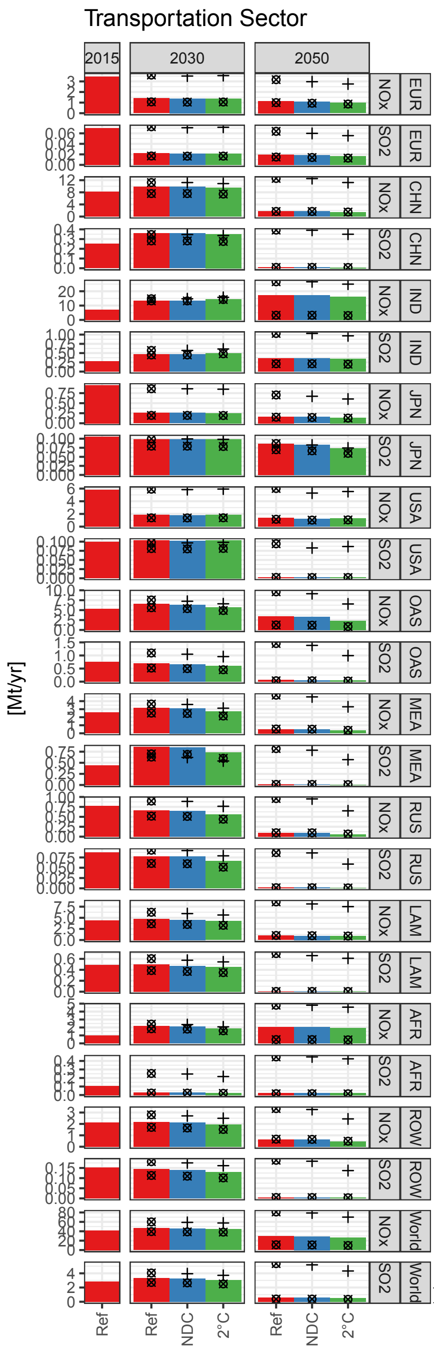


Figure SI-11: VOC emissions for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent and AP_FE sensitivity cases.

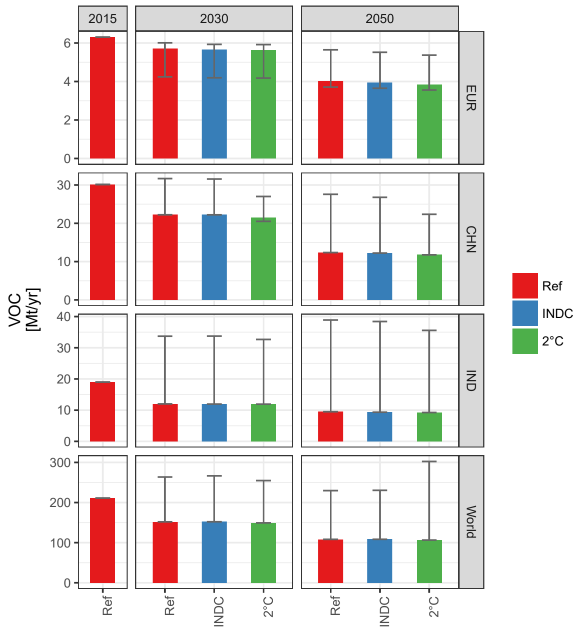


Figure SI-12: OC emissions for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent and AP_FE sensitivity cases.

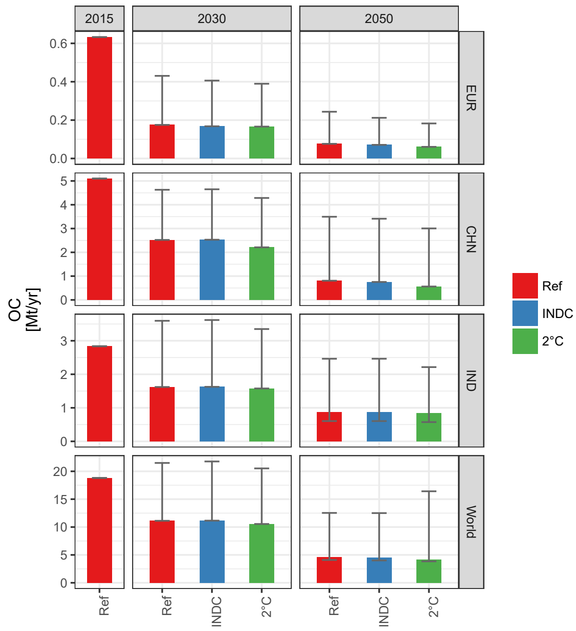


Figure SI-13: CH4 emissions for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent and AP_FE sensitivity cases.

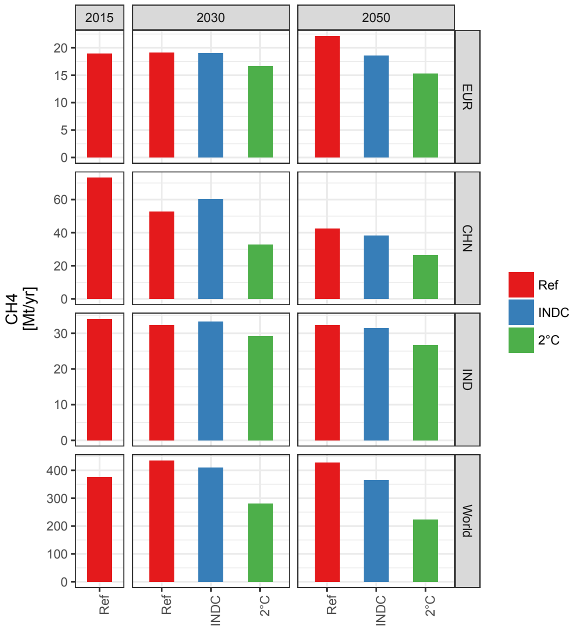


Figure SI-14: CO emissions for the Reference, NDC and 2°C scenario for EUR (Europe), CHN (China), IND (India) and the World in 2015, 2030 and 2050. Bars represent values for the AP_trend air pollution control scenario, markers represent the AP_stringent and AP_FE sensitivity cases.

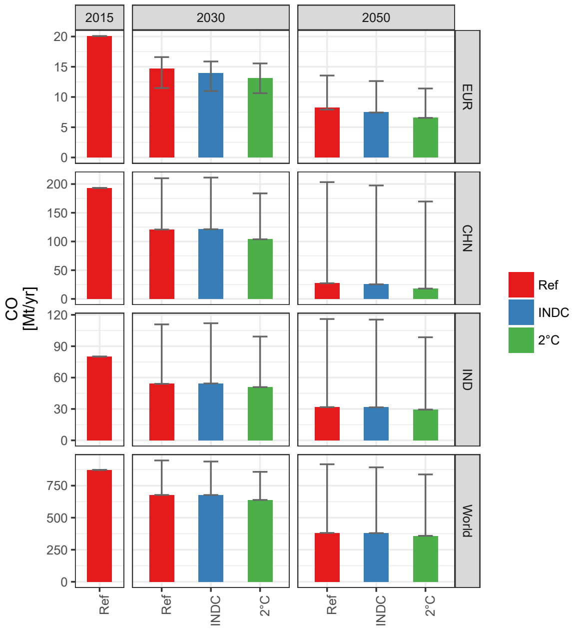


Figure SI-15: Global sectoral BC emissions for the Reference, NDC and 2°C scenario.

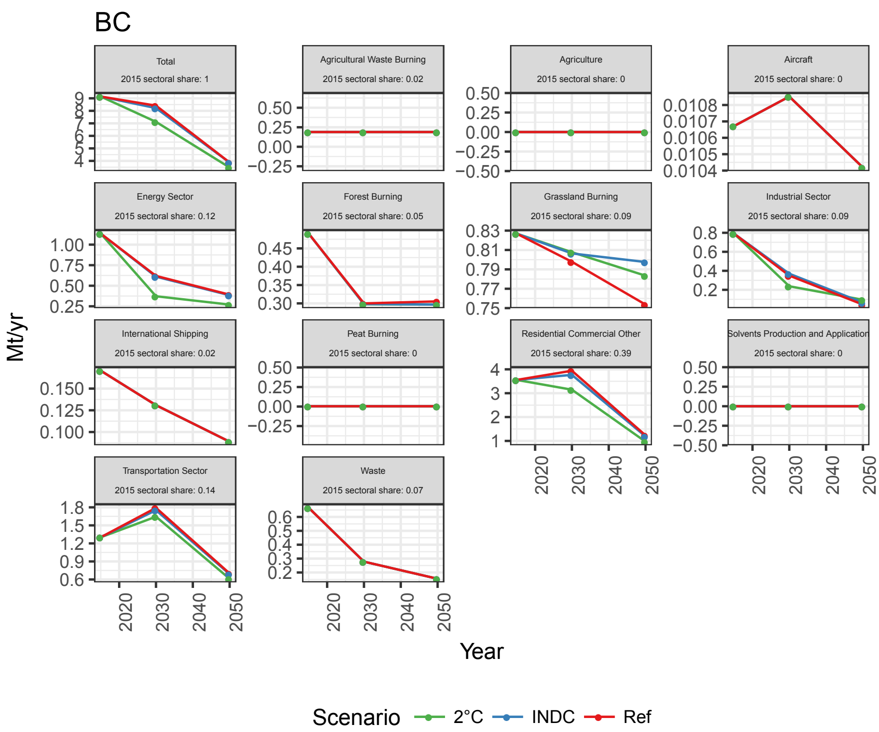


Figure SI-16: Global sectoral SO2 emissions for the Reference, NDC and 2°C scenario.

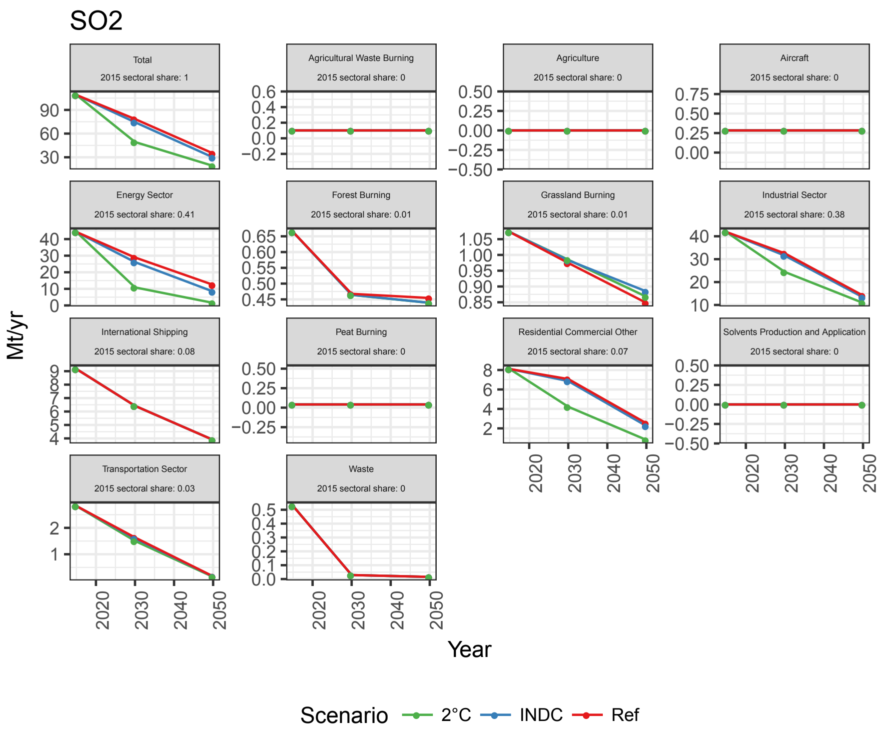


Figure SI-17: Global sectoral NOx emissions for the Reference, NDC and 2°C scenario.

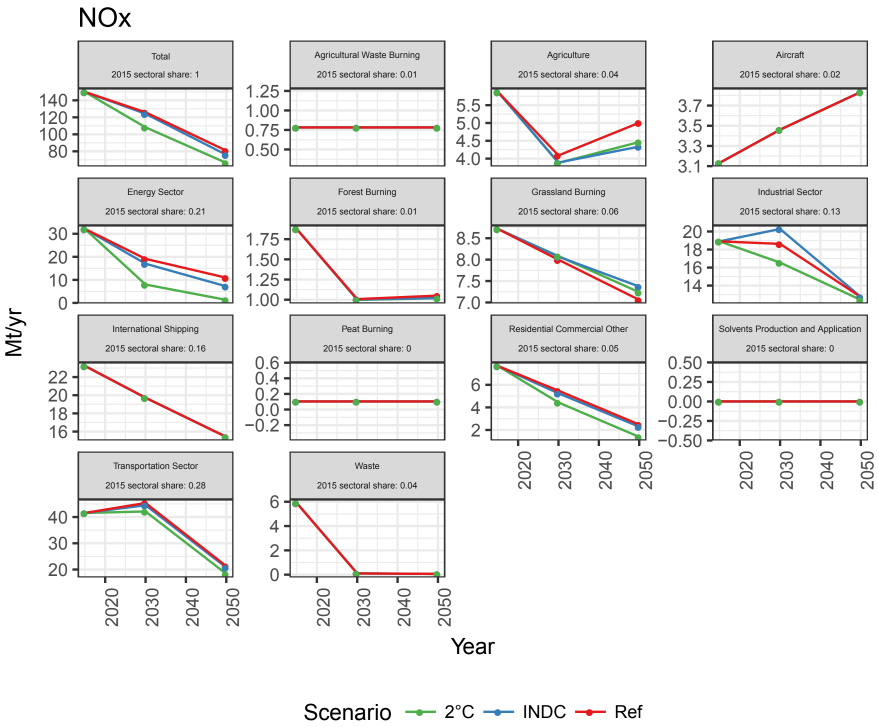


Figure SI-18: Global sectoral VOC emissions for the Reference, NDC and 2°C scenario.

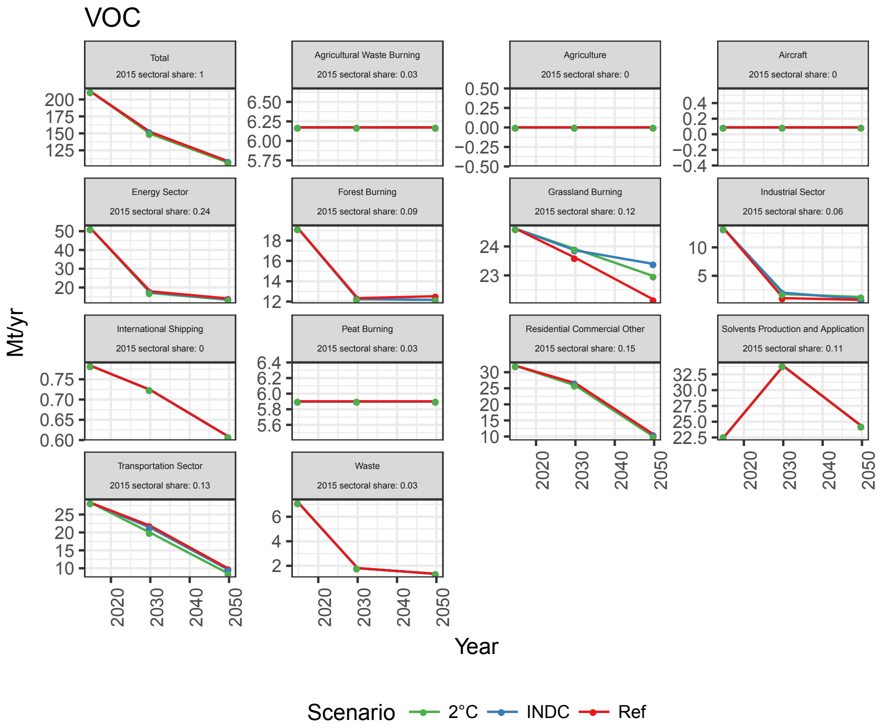


Figure SI-19: Global sectoral OC emissions for the Reference, NDC and 2°C scenario.

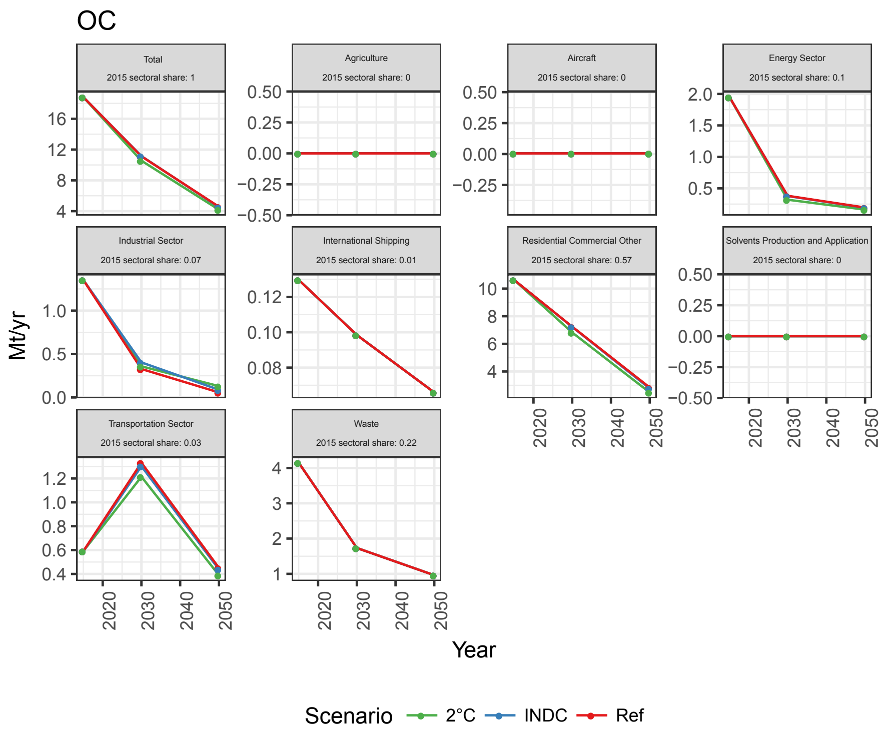


Figure SI-20: Global sectoral CH4 emissions for the Reference, NDC and 2°C scenario.

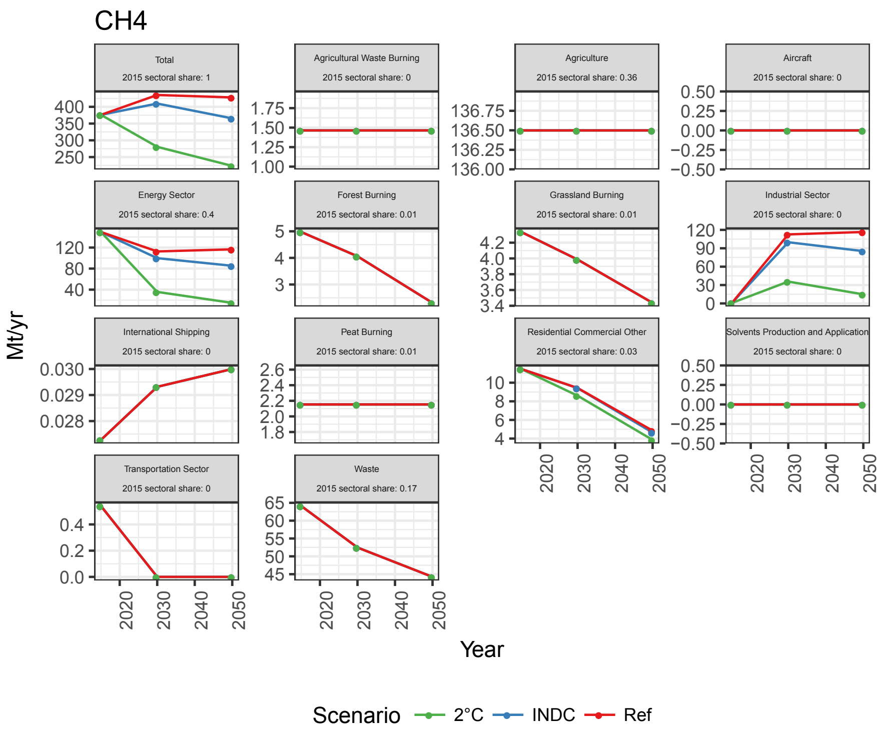
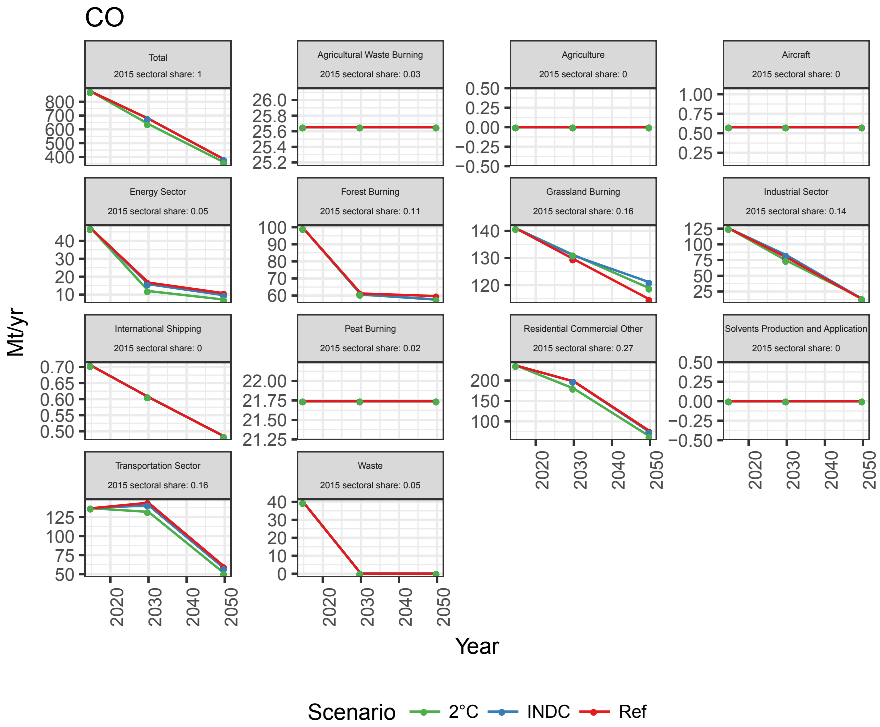


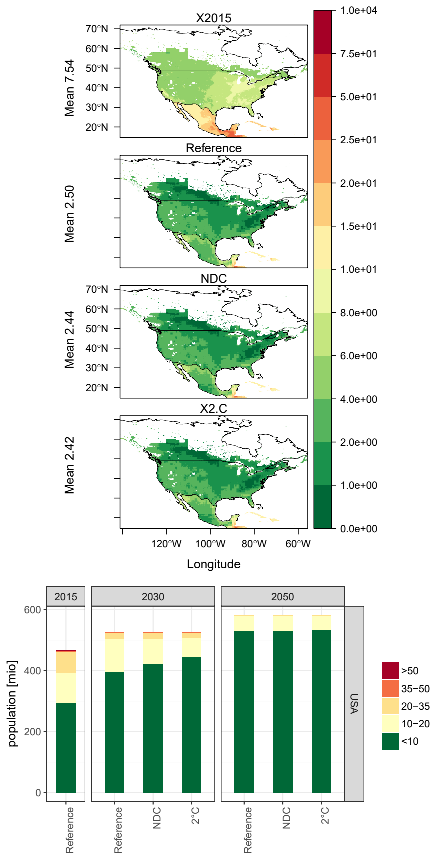
Figure SI-21: Global sectoral CO emissions for the Reference, NDC and 2°C scenario.



SI-1.2.3. Air Chemistry Modeling

Figure SI-22: Mean annual $PM_{2.5}$ concentration [$\mu g/m^3$] for the year 2015 and 2050 of the NDC and 2°C scenario and AP_trend air pollution control case for the USA and Latin America. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange), 35>x>20 $\mu g/m3$ (light orange), 20>x>10 $\mu g/m3$ (yellow) and <10 $\mu g/m3$ (green)

(a) USA



(b) Latin America

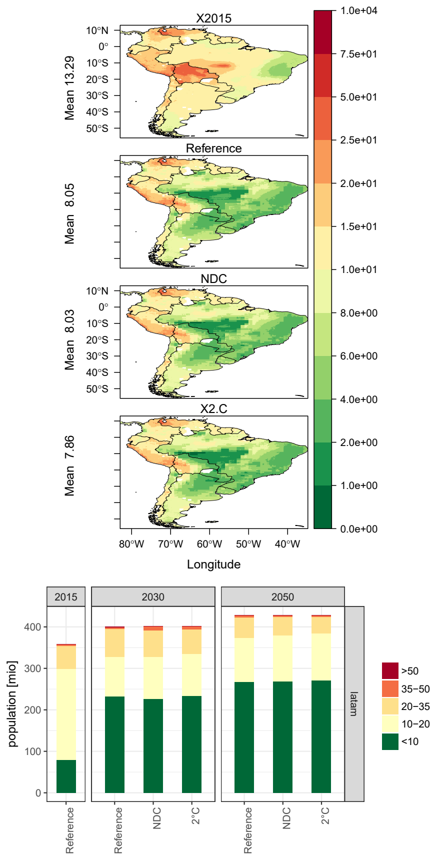
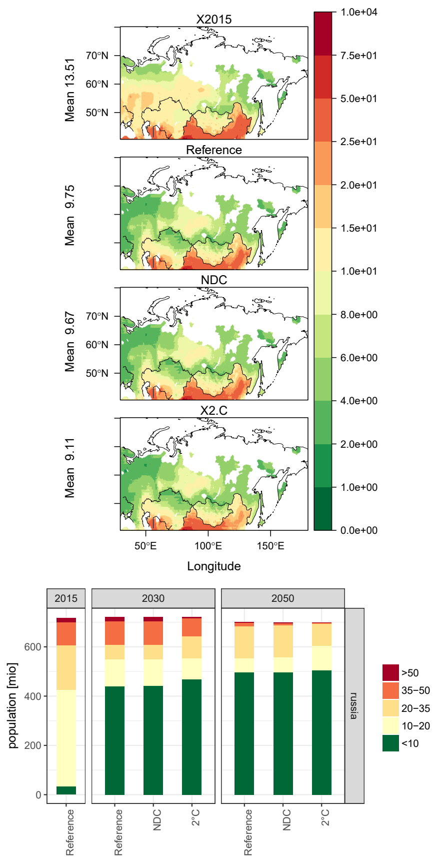


Figure SI-23: Mean annual $PM_{2.5}$ concentration $[\mu g/m^3]$ for the year 2015 and 2050 of the NDC and 2°C scenario and AP_trend air pollution control case for Russia and the Middle East. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange), 35>x>20 $\mu g/m3$ (light orange), 20>x>10 $\mu g/m3$ (yellow) and <10 $\mu g/m3$ (green)

(a) Russia



(b) Middle East

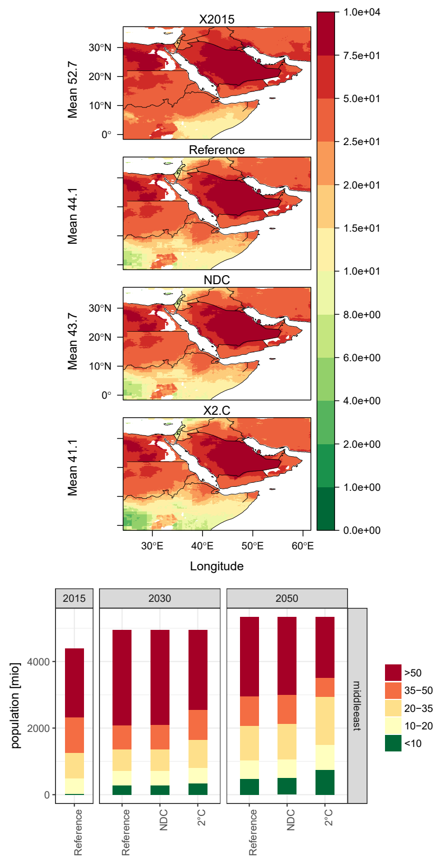
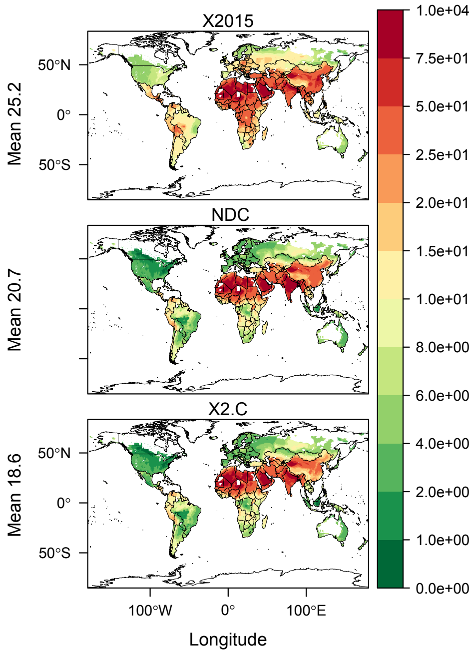
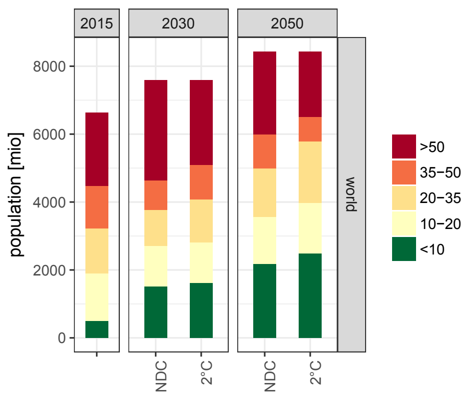


Figure SI-24: Global mean annual $PM_{2.5}$ concentration [$\mu g/m^3$] for the year 2015 and 2050 of the NDC and 2°C scenario and AP_trend air pollution control case. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange), 35>x>20 $\mu g/m3$ (light orange), 20>x>10 $\mu g/m3$ (yellow) and <10 $\mu g/m3$ (green)





SI-1.2.4. Health impact assessment

Figure SI-25: Health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths $[cases/km^2]$ for the year 2015 and relative to 2015 for the year 2050 of the NDC and 2°C scenario and AP_trend air pollution control case for the USA and Latin America. Bars represent values for

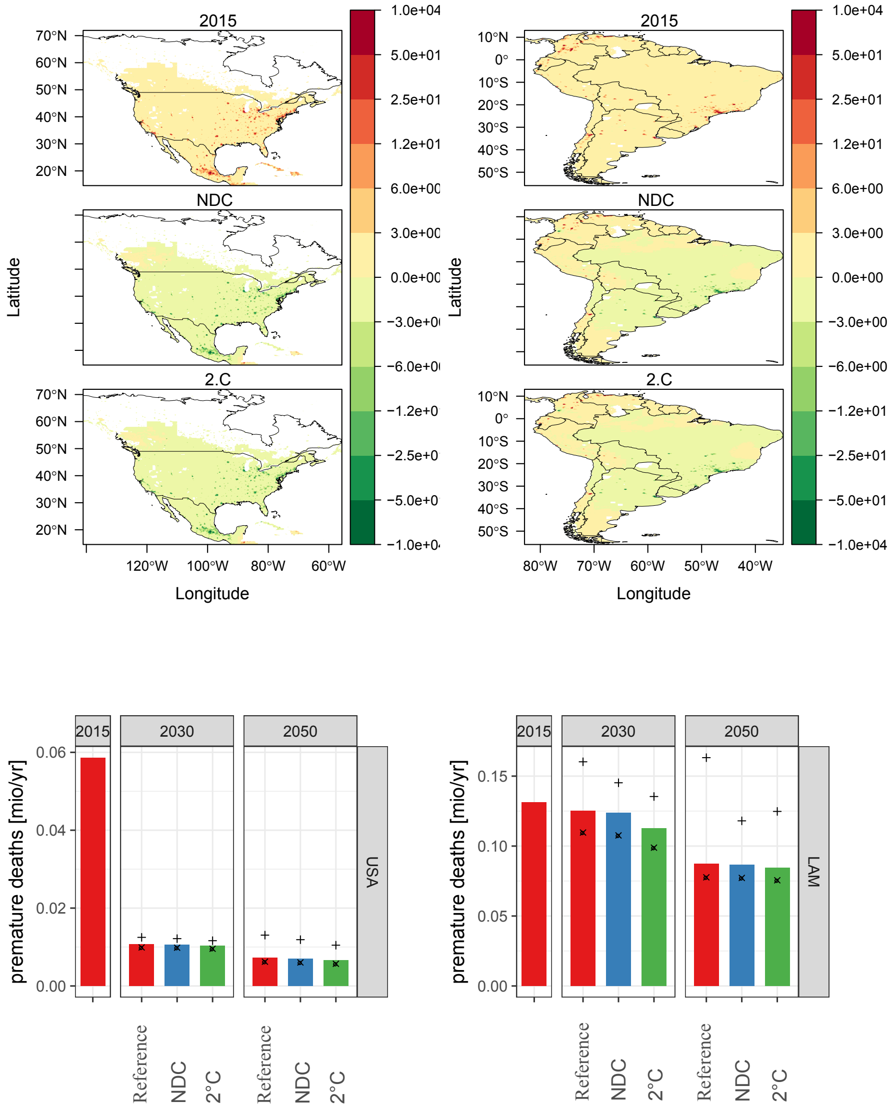


Figure SI-26: Health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths $[cases/km^2]$ for the year 2015 and relative to 2015 for the year 2050 of the NDC and 2°C scenario and AP_trend air pollution control case for Russia and the Middle East. Bars represent values for

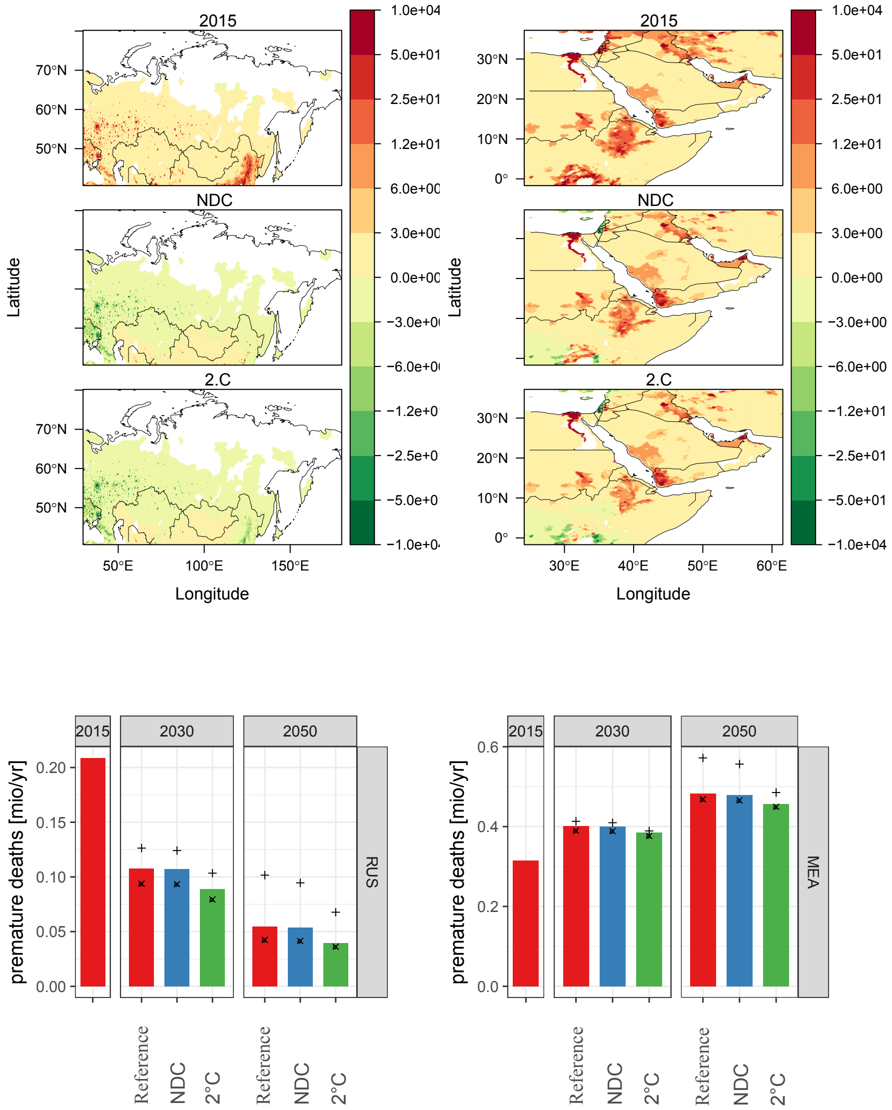


Figure SI-27: Global health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths $[cases/km^2]$ for the year 2015 and relative to 2015 for the year 2050 of the NDC and 2°C scenario and AP_trend air pollution control case. Bars represent values for the AP_trend air pollution control scenario, markers represent net costs in the AP_stringent (⊗) and AP_FE (+) sensitivity cases.

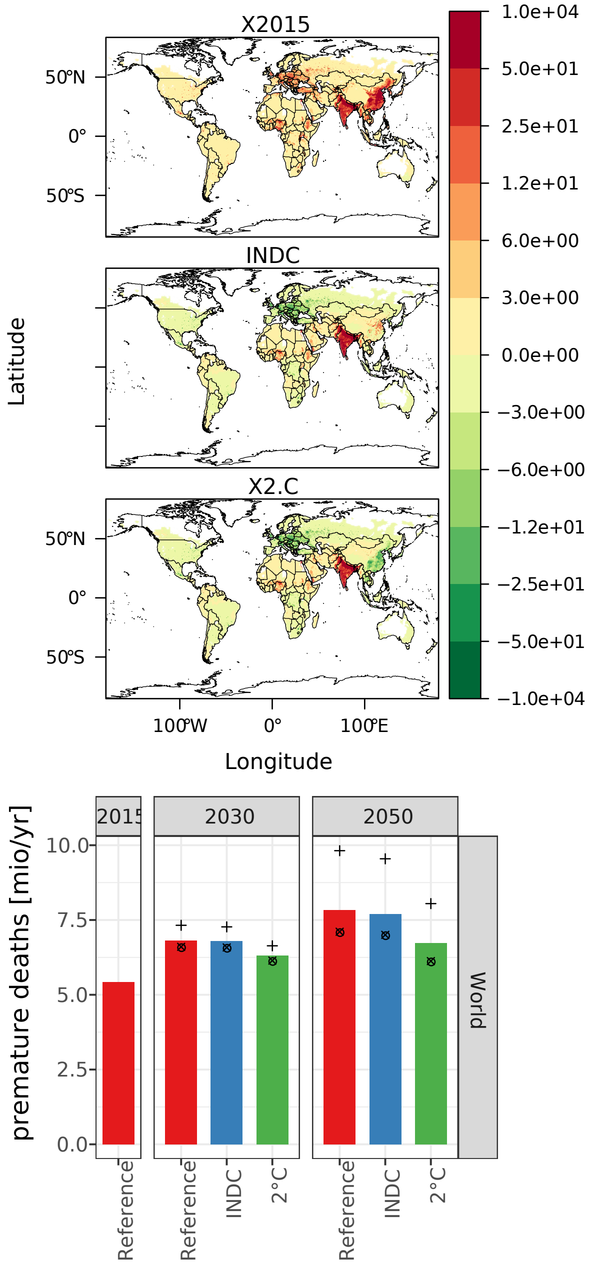
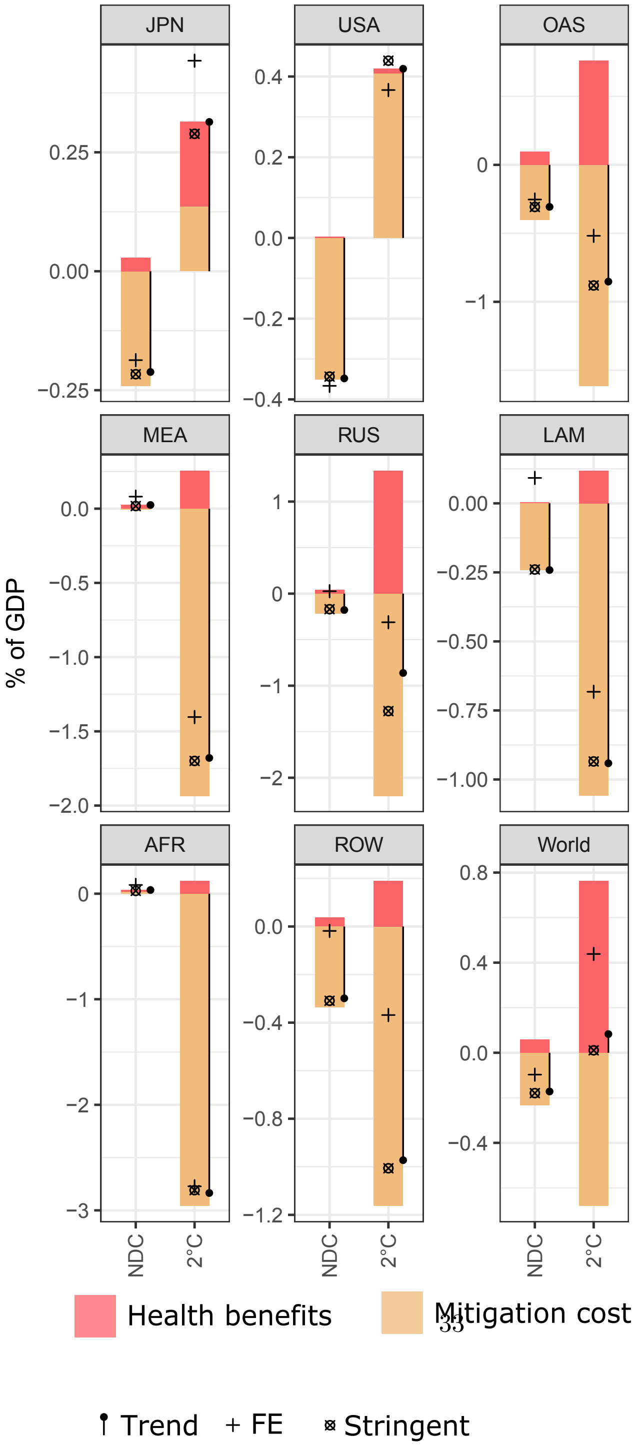
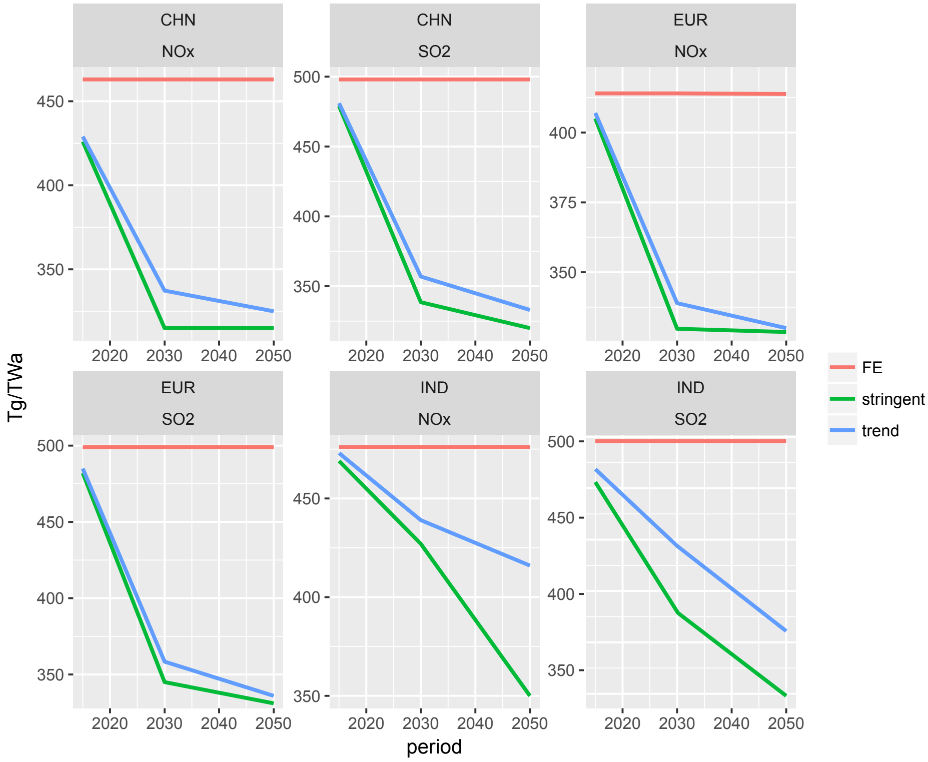


Figure SI-28: Climate change mitigation costs (yellow), monetized avoided health damages (red) and net social costs for the AP_trend (•), AP_stringent (⊗) and AP_FE (+) cases for the regions JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World. Amounts are cumulated over 2015-2050, discounted at 5% and expressed relative to cumulated and discounted GDP PPP.



SI-1.2.5. Emission factors

Figure SI-29: SO2 and NOx emission factor development for the aggregate stock of electricity generation from coal in 2015-2050 for CHN (China), IND (India) and EUR (Europe).



Aboumahboub T, Luderer G, Kriegler E et al (2014) On The Regional Distribution Of Climate Mitigation Costs: The Impact Of Delayed Cooperative Action. Climate Change Economics 05:1440002. doi: 10.1142/S2010007814400028

Alberini A, Bateman I, Loomes G, Ščasný M (2010) Valuation of environment-related health risks for children. OECD Publishing

Aldy JE, Viscusi WK (2007) Age Differences in the Value of Statistical Life: Revealed Preference Evidence. Review of Environmental Economics and Policy 1:241–260. doi: 10.1093/reep/rem014

Amann M (2012) Greenhouse gas and air pollution interaction and synergies (GAINS). 0–43

Anenberg SC, Horowitz LW, Tong DQ, West JJ (2010) An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environmental Health Perspectives 118:1189–1195. doi: 10.1289/ehp.0901220

Anenberg SC, Miller J, Minjares R et al (2017) Impacts and mitigation of excess diesel-related NO x emissions in 11 major vehicle markets. Nature 545:467–471. doi: 10.1038/nature22086

Bauer N, Baumstark L, Leimbach M (2012) The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds. Climatic Change 114:145–168. doi: 10.1007/s10584-011-0129-2

Bauer N, Edenhofer O, Kypreos S (2008) Linking energy system and macroeconomic growth models. Computational Management Science 5:95–117. doi: 10.1007/s10287-007-0042-3

Burnett R, Chen H, Szyszkowicz M et al (2018) Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proceedings of the National Academy of Sciences 115:9592–9597. doi: 10.1073/pnas.1803222115

Burnett RT, Arden Pope C, Ezzati M et al (2014) An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environmental Health Perspectives 122:397–403. doi: 10.1289/ehp.1307049

Cohen AJ, Brauer M, Burnett R et al (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lancet 389:1907–1918. doi: 10.1016/S0140-6736(17)30505-6

Deng HM, Liang QM, Liu LJ, Anadon LD (2017) Co-benefits of greenhouse gas mitigation: A review and classification by type, mitigation sector, and geography. Environmental Research Letters 12: doi: 10.1088/1748-9326/aa98d2

Duncan G (2014) After neo-liberalism, what could be worse? New Zealand Sociology 29:15–39. doi: 10.1073/pnas.1809474115

Gao J, Kovats S, Vardoulakis S et al (2018) Science of the Total Environment Public health co-benefits of greenhouse gas emissions reduction : A systematic review. Science of the Total Environment 627:388–402. doi: 10.1016/j.scitotenv.2018.01.193

Gidden MJ, Fujimori S, Berg M van den et al (2018) A methodology and implementation of automated emissions harmonization for use in Integrated

Assessment Models. Environmental Modelling and Software 105:187–200. doi: 10.1016/j.envsoft.2018.04.002

Harmsen M et al (2019) Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers' mitigation. Climatic Change. doi: 10.1007/s10584-019-02436-3

Heft-Neal S, Burney J, Bendavid E, Burke M (2018) Robust relationship between air quality and infant mortality in Africa. Nature 559:254–258. doi: 10.1038/s41586-018-0263-3

Hoesly RM, Smith SJ, Feng L et al (2018) Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geoscientific Model Development 11:369–408. doi: 10.5194/gmd-11-369-2018

Jerrett M, Burnett RT, Pope CA et al (2009) Long-Term Ozone Exposure and Mortality. New England Journal of Medicine 360:1085–1095. doi: 10.1056/NEJMoa0803894

Jones B, O'Neill BC (2016) Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environmental Research Letters 11:084003. doi: 10.1088/1748-9326/11/8/084003

KC S, Lutz W (2017) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42:181–192. doi: 10.1016/j.gloenvcha.2014.06.004

Krupnick A (2008) Mortality-Risk Valuation and Age: Stated Preference Evidence. Ssrn 1:261–282. doi: 10.1093/reep/rem016

Landrigan PJ, Fuller R, Acosta NJ et al (2018) The Lancet Commission on pollution and health. The Lancet 391:462–512. doi: 10.1016/S0140-6736(17)32345-0

Leimbach M, Bauer N, Baumstark L, Edenhofer O (2010) Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. Environmental Modeling and Assessment 15:155–173. doi: 10.1007/s10666-009-9204-8

Li C, McLinden C, Fioletov V et al (2017) India Is Overtaking China as the World's Largest Emitter of Anthropogenic Sulfur Dioxide. Scientific Reports 7:1–7. doi: 10.1038/s41598-017-14639-8

Li M, Zhang D, Li C-T et al (2018) Air quality co-benefits of carbon pricing in China. Nature Climate Change 8:398–403. doi: 10.1038/s41558-018-0139-4

Luderer G, Bertram C, Calvin K et al (2016) Implications of weak near-term climate policies on long-term mitigation pathways. Climatic Change 136:127–140. doi: 10.1007/s10584-013-0899-9

Markandya A, Sampedro J, Smith SJ et al (2018) Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. The Lancet Planetary Health 2:e126–e133. doi: 10.1016/S2542-5196(18)30029-9

OECD (2012) Mortality risk valuation in environment, health and transport policies. OECD Publishing

O'Neill BC, Kriegler E, Ebi KL et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42:169–180. doi: 10.1016/j.gloenvcha.2015.01.004

Rafaj P, Schöpp W, Russ P et al (2012) Co-benefits of post-2012 global climate mitigation policies. doi: 10.1007/s11027-012-9390-6

Rao S, Klimont Z, Leitao J et al (2016) A multi-model assessment of the co-benefits of climate mitigation for global air quality. Environmental Research Letters 11:124013. doi: 10.1088/1748-9326/11/12/124013

Rao S, Klimont Z, Smith SJ et al (2017) Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change 42:346–358. doi: 10.1016/j.gloenvcha.2016.05.012

Riahi K, Dentener F, Gielen D et al (2012) Energy Pathways for Sustainable Development. In: Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L (eds) Global energy assessment (gea). Cambridge University Press, Cambridge, pp 1205–1306

Rogelj J, Fricko O, Meinshausen M et al (2017) Understanding the origin of Paris Agreement emission uncertainties. Nature Communications 8:15748

Shaddick G, Thomas ML, Green A et al (2018) Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution. Journal of the Royal Statistical Society Series C: Applied Statistics 67:231–253. doi: 10.1111/rssc.12227

Smith SJ, Chateau J, Dorheim K et al Impact of Methane and Black Carbon Mitigation on Forcing and Temperature : A Multi-Model Scenario Analysis. this issue

Stanaway JD, Zhou M, Zimsen SRM et al (2018) Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Stu. The Lancet 392:1923–1994. doi: 10.1016/S0140-6736(18)32225-6

The Lancet Neurology (2018) Air pollution and brain health: an emerging issue. The Lancet Neurology 17:117. doi: 10.1016/S1474-4422(17)30462-3

United Nations Environment Programme (2018) UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi

Van Dingenen R, Dentener F, Crippa M et al (2018) TM5-FASST: A global atmospheric source-receptor model for rapid impact analysis of emission changes on air quality and short-lived climate pollutants. Atmospheric Chemistry and Physics 18:16173–16211. doi: 10.5194/acp-18-16173-2018

Vandyck T, Keramidas K, Kitous A et al (2018) Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. Nature Communications 9:1–11. doi: 10.1038/s41467-018-06885-9

Viscusi WK (2010) The heterogeneity of the value of statistical life: Introduction and overview. Journal of Risk and Uncertainty 40:1–13. doi: 10.1007/s11166-009-9083-z

Vuuren DP van, Lucas PL, Hilderink H (2007) Downscaling drivers of global environmental change: Enabling use of global SRES scenarios at the national and grid levels. Global Environmental Change 17:114–130. doi: 10.1016/j.gloenvcha.2006.04.004

Wang H, Naghavi M, Allen C (2016) Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the Global Burden of Disease Study 2015. The Lancet 388:1459–1544. doi: 10.1016/S0140-6736(16)31012-1

West JJ, Smith SJ, Silva RA et al (2013) Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nature Climate Change 3:885–889. doi: 10.1038/nclimate2009

WHO (2016) Modelled Global Ambient Air Pollution estimates

World Health Organization (2012) WHO Mortality Database

Xie Y, Dai H, Xu X et al (2018) Co-benefits of climate mitigation on air quality and human health in Asian countries. Environment International 119:309–318. doi: 10.1016/j.envint.2018.07.008

Chapter 3

Holistic energy system modeling combining multi-objective optimization and life cycle assessment*

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LETTER

Holistic energy system modeling combining multi-objective optimization and life cycle assessment

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Abstract

Making the global energy system more sustainable has emerged as a major societal concern and policy objective. This transition comes with various challenges and opportunities for a sustainable evolution affecting most of the UN's Sustainable Development Goals. We therefore propose broadening the current metrics for sustainability in the energy system modeling field by using industrial ecology techniques to account for a conclusive set of indicators. This is pursued by including a life cycle based sustainability assessment into an energy system model considering all relevant products and processes of the global supply chain. We identify three pronounced features: (i) the low-hanging fruit of impact mitigation requiring manageable economic effort; (ii) embodied emissions of renewables cause increasing spatial redistribution of impact from direct emissions, the place of burning fuel, to indirect emissions, the location of the energy infrastructure production; (iii) certain impact categories, in which more overall sustainable systems perform worse than the cost minimal system, require a closer look. In essence, this study makes the case for future energy system modeling to include the increasingly important global supply chain and broaden the metrics of sustainability further than cost and climate change relevant emissions.

Nomenclature

a	partitioned process vector of A
A	technology matrix
b	partitioned process vector of B
B	intervention matrix
c	cost
d	discount rate
ESM	energy system model
f	final demand vector
g	inventory vector
GDP	gross domestic product
GHG	greenhouse gas
h	impact vector
i	flow
IPCC	Intergovernmental Panel on Climate Change
j	process
k	environmental intervention
l	impact category
LCA	life cycle assessment
LCI	life cycle inventory
MOr-OSA	Multi-Objective Optimization Sustainability Assessment
n	power plant number
n_{bh}	modeled hours of the modeling period
p	power
P	process vector
Q	characterization matrix
RES-E	renewable energy sources of electricity
s	scaling vector
S	feasible region in the solution space
SI	supplementary information
tec	technology type
u	availability factor
x	vector of decisions variables
α	depreciation period
η	efficiency factor
λ	modeling period
χ	binary decisions variables
φ	commission year

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Introduction

Climate change is one of the most important issues faced by global society in the 21st century. The magnitude of its contribution predetermines the energy supply sector as a key field of action due to the necessary transformation from a fossil fuel to a renewable based system. Energy policy is of great significance to energy systems, especially for the projected transition to a decarbonized sustainable energy supply. Policymakers usually need to establish policies based on a detailed assessment of competing technologies informed through energy system modeling. The common approach in energy system analysis is to model cost-optimal energy scenarios while constraining greenhouse gas (GHG) emissions. However, with an ever-increasing share of renewable energy sources of electricity (RES-E) this approach fails to account for other burdens and benefits associated with the deployment of power infrastructure and the operation of the power system. These co-burdens and benefits include, among many others, air pollution, public health effects (Lelieveld *et al* 2015, Rao *et al* 2016, West *et al* 2013), the water–energy–land nexus (Howells *et al* 2013) and biodiversity conservation (Gasparatos *et al* 2017, de Baan *et al* 2013, Gibon *et al* 2017). Consequently, the consideration of GHG emissions as the unique metric is not suitable for a holistic sustainability assessment. This is acknowledged on an international level by numerous organizations such as the World Energy Council, speaking of the 'Energy Trilemma' (World Energy Council 2016), the European Commission stating that the 'People's well-being, industrial competitiveness and the overall functioning of society are dependent on safe, secure, sustainable and affordable energy.' (European Commission 2011), and the Intergovernmental Panel on Climate Change (IPCC) specifying, 'Climate policy intersects with other societal goals creating the possibility of co-benefits or adverse side-effects. [...] This multi-objective perspective is important in part because it helps to identify areas where support for policies that advance multiple goals will be robust.' (Intergovernmental Panel on Climate Change 2014). Another recent prominent example is the formulation of the 17 Sustainable Development Goals by the UN. The 2030 Agenda for Sustainable Development seeks to achieve various targets such as building resilient infrastructure, ensuring access to clean energy and protecting sustainable use of ecosystems (United Nations 2015).

These examples elucidate the requirement of future energy system modeling to be capable of answering questions concerning not only the economic but also the environmental dimension. Seconding these arguments, the scientific community increasingly calls for an integrated assessment of these two dimensions, represented through the energy system and industrial ecology communities. (Liu *et al* 2015, Pauliuk *et al* 2017, Newlands 2016) Furthermore, the increasing relevance of the spatial aspects, which come with the shift of the environmental impacts from the point of converting chemical to electrical energy to the manufacturing of these technologies, emphasizes the need for a comprehensive assessment, including the whole global supply chain. (Laurent and Espinosa 2015, Daly *et al* 2015) We address these calls with an integrated life cycle based sustainability assessment combined with an energy system model (ESM) and apply this framework to the German power system expansion problem as a case study.

Various studies exist that use life cycle assessment (LCA) to examine the environmental impacts of electricity production from a product perspective (Turconi *et al* 2013, Varun *et al* 2009) or analyze the impacts of changed energy systems through scenario analysis (Gibon *et al* 2015, Kouloumpis *et al* 2015, Berrill *et al* 2016, Santoyo-Castelazo and Azapagic 2014b, Barteczko-Hibbert *et al* 2014). However, standard LCA models are static and linear, hence, lack relevance for identifying the optimal future mix of technology options and are unable to give insight concerning time-dependent decisions (Ekvall *et al* 2007). The necessary endogenous integration of the LCA into an ESM is missing (the decision of the ESM affects the LCA), suitable for answering key questions about the future energy supply.

The inclusion of the non-monetized life cycle based impacts into the optimization as well as developing the whole set of desirable solutions for decision makers is not possible with single objective ESMs and requires an extension to a multi-objective approach. Studies with a more comprehensive sustainability assessment are categorized according to the phase of decision maker inclusion (Hwang and Masud 1979) into the *a priori* (Oliveira and Antunes 2004, Meyerhoff *et al* 2010, Söderholm and Sundqvist 2003, Zhang *et al* 2007, Kim 2007, Gujba *et al* 2011, Wiser *et al* 2016a, 2016b, Stamford and Azapagic 2012, Treyer *et al* 2014, Gibon *et al* 2015, Shmelev and van den Bergh 2016, Atilgan and Azapagic 2016, Hertwich *et al* 2015), the interactive (Heinrich *et al* 2007, Karger and Hennings 2009, Kowalski *et al* 2009, Oliveira and Antunes 2004, Santoyo-Castelazo and Azapagic 2014a, Schenler *et al* 2009), and the *a posteriori* methods. The main drawback of the *a priori* assessment of energy scenarios is the fact that only cost optimal solutions are assessed for their environmental impact: the LCA dimension is not considered in the optimization or only enforced through emission limits i.e. additional constraints. Most importantly, however, only the *a posteriori* calculates the full spectrum of efficient solutions, called the Pareto front. This allows the decision maker to select the most preferred solution while being aware of the trade-off between the different systems. The relevance of this is acknowledged by the IPCC stating that '[...] a comprehensive exploration of the solution space [...] recognizes that mitigation itself is only one objective among others for decision makers.' (Pachauri *et al* 2014) There are examples in other fields of research

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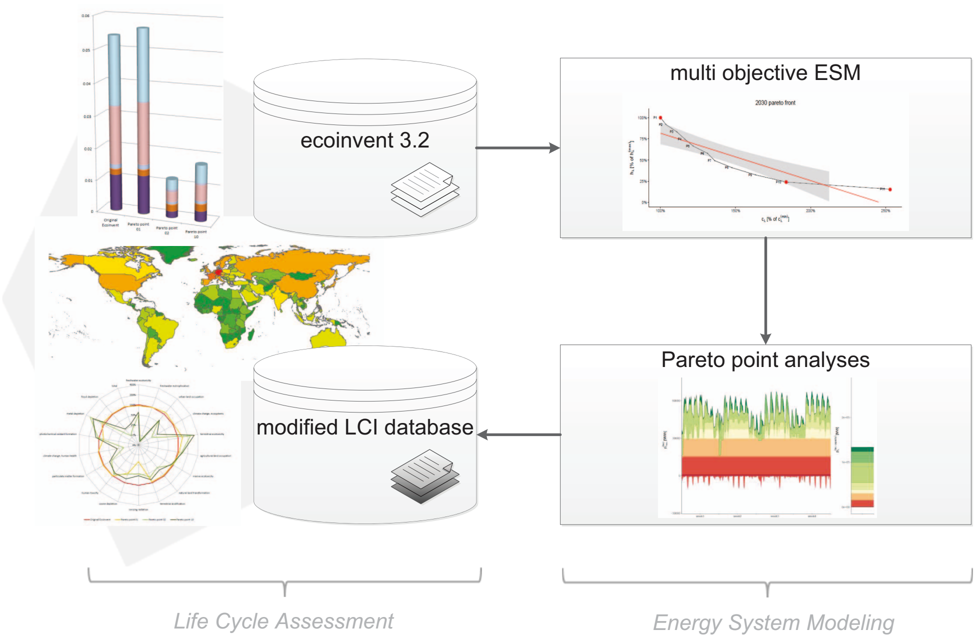

Figure 1. Schematic of the general structure of MOrOSA. MOrOSA is a hybrid model combining ESM and LCA. The LCI database Ecoinvent 3 in conjunction with the impact assessment methodology of ReCiPe provides the technology specific impact indicator for the multi-objective ESM. One or more solutions of the resulting Pareto front of efficient solutions can then be analyzed in more detail with regard to capacity, commitment, costs, and LCA impacts.

for studies combining *a posteriori* multi-objective optimization with an LCA based sustainability assessment (Ingle and Lakade 2016, Gebreslassie *et al* 2009, Pieragostini *et al* 2012, Azapagic and Clift 1999, Azapagic 1999, Gerber *et al* 2011). In the ESM community, such models lack the foundation of the sustainability assessment based on the LCA methodology (Mavrotas *et al* 2008, Fazlollahi *et al* 2012, Buoro *et al* 2013, Sütő *et al* 2015) or consider systems very limited in systemic, spatial and temporal scope (Santoyo-Castelazo and Azapagic 2014b, Gebreslassie *et al* 2009, Pieragostini *et al* 2012, Azapagic 1999, Azapagic and Clift 1999).

Therefore, the aim of this study is to tackle the challenges mentioned above through the developed MOrOSA (Multi-Objective Optimization Sustainability Assessment) energy system model. The *a posteriori* model combines a detailed capacity expansion and unit commitment modeling with a multi-objective algorithm and an endogenously integrated elaborated LCA into a hybrid ESM. We illustrate this approach by applying MOrOSA to the capacity expansion and unit commitment problem of the German power system of 2030. Germany is chosen predominantly because of its prominent role in deploying renewable based power infrastructure, the importance of the production industry, the global integration of the economy, and its potential model role. The year 2030 serves as an intermediate time horizon on the way to a decarbonized energy supply while accounting for the current capital stock and avoiding over- or underestimation of long-term trends due to the partial-equilibrium formulation.

Methods

Figure 1 illustrates the structure of the MOrOSA framework. The model consists of the two main parts: energy system modeling and life cycle assessment. See appendix A for a detailed formulation of the ESM and appendix B for the LCA framework. As a general process, the LCA database is providing the technology specific impact indicators to the ESM. Then, the multi-objective optimization is performed utilizing these single score indicators, which can include several normalized and weighted impact categories. The resulting Pareto front provides an approximation of all efficient solutions which can then be selected for detailed analyses. The systemic characteristics of these points, each representing a potential future energy system, are fed back into the LCA database. The separation of the cost and impact in terms of fixed and variable portions facilitates the endogenous integration into the ESM. In contrast to the common approach of using unchanged LCA from the literature, this method avoids possible inconsistencies, for example concerning the development of full load hours not fed back into the LCA.

As stated above, the transition from a conventional technology-based system to an increased share of

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RES-E generation shifts the environmental impact from the process of generating electricity to the production of the generation technologies itself. The premise for developing the ESM is, therefore, to achieve a detailed power system operation while including the capacity expansion. Consequently, the model is designed as a partial equilibrium model formulated as a mixed integer linear programming problem with the focus on a detailed representation of the power system operation. Traditionally, the capacity expansion models neglected a detailed operation of the system, the reason being that the combination of a capacity expansion and a unit commitment quickly becomes intractable due to the computational complexity. However, the improvements in computational power as well as in the applied solvers facilitate the integration of both models (Rosen *et al* 2007, Kamalinia *et al* 2011, Ma *et al* 2013, Pina *et al* 2013, Flores-Quiroz *et al* 2016).

Presenting the whole picture of optimal solutions requires the efficient generation of the approximation of the Pareto front. The Pareto front consists of non-dominated solutions; this means that it is not possible to enhance the solution in one dimension without worsening it on another dimension. Therefore, instead of calculating one single optimal solution, a sufficient number of grid points approximating the Pareto front is required. This considerably raises the computational burden. Accordingly, the design of the multi-objective algorithm plays a crucial role in achieving an applicable modeling framework, see appendix A for details.

The electricity system expansion problem of Germany

The developed hybrid modeling framework is applied to the electricity system capacity expansion problem with Germany as a modeling region. The result encompasses the built/decommissioned capacity and its commitment in the modeling period λ of 2030 with 2015 as the base year. The modeled hours of the modeling period λ_{nbh} are four weeks of representative seasonal time slices with a total number of 672 h. See appendix C for a detailed description of the data sources and assumptions.

The electricity supply as well as the associated environmental impacts are separated into a fixed and a variable portion. The fixed portion reflects the cost and impact associated with the production and construction of the power generation infrastructure as well as all the upstream processes necessary, for example steel production and land transformation for the construction of a coal power plant. The variable portion on the other hand represents costs and impacts caused by the generation of electricity itself, for example mining and burning of coal. The emissions are based on the ecoinvent 3.2 LCA database encompassing about 13 000 production processes and 2000 emissions (Treyer and Bauer 2016) covering 89% of the global electricity production. These environmental interventions are translated into impacts using the widely accepted ReCiPe methodology (Goedkoop and Huijbregts 2013). This impact assessment methodology considers 17 midpoint indicators that can be converted into a single score by the use of a weighting procedure (see appendices A and B for details on the energy system model and LCA approach). All data and assumptions are available in the supplementary information (SI) available at stacks.iop.org/ERL/12/124005/mmedia, and in the code of the LCA method at https://doi.org/10.5281/zenodo.1010461.

The Pareto front of efficient solutions is shown in figure 2 (top left) (SI folder results 'pareto_front'). Every point represents a power system in 2030. The single score ReCiPe based LCA indicator h_λ and the cost c_λ are plotted relative to the cost optimal system, represented by P1. The Pareto front represents the trade-offs between cost and impact. Following the curve from P1−P11 (going from cost optimal to an increased consideration of impacts) reveals an initially relatively steep decrease of the LCA impact compared to the increase in cost, representing the low hanging fruit of impact mitigation. This decrease levels out starting from P7 and the last step from P10−P11 comes with a comparably high increase in cost. As stated above, the *a posteriori* method presents an approximation of the full spectrum of non-dominated systems. The nature of the solutions of being non-dominated requires a decision maker to choose the desired system according to a set of preferences. For the purpose of this study P10 is selected as a desirable system configuration. This low impact system is able to cut the impact by a factor of four with an increase of cost of 84%. Understanding the effect of the LCA impact consideration on the resulting system requires a detailed analysis. This is applied to the two extreme points P1, P11, and the selected low impact system P10. Figure 2 shows the resulting capacity in 2030 aggregated over the different technologies *tec* on the right side and the commitment of this capacity on the left side for each of these three points (SI folder results 'capacity_generation_2030_p01, _p10, _p11'). They significantly differ in total capacity as well as in the technological structure: the overall capacity almost doubles in P11 compared to P1, an effect of the considerably lower possible full load hours of renewables. The conventional technologies mainly differ in the increased decommissioning of lignite and coal and an increased resulting capacity of gas in P10 and P11. The RES-E technologies show a clear trend with a considerably higher capacity in P10 and P11 compared to P1. Solar photovoltaic (PV), wind and biogas all at least double their capacity, with wind >3 MW, wind offshore and ground mounted solar PV almost tripling. The changing capacity structure is reflected in the generation pattern: the massive expansion of RES-E pushes

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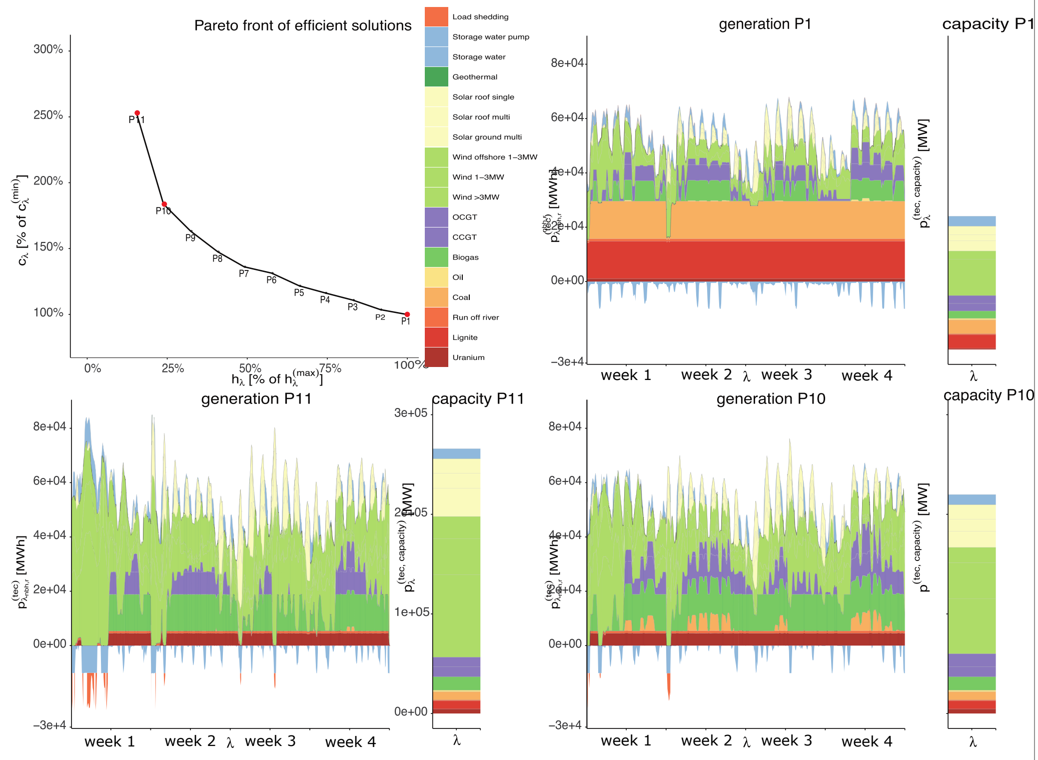

Figure 2. Pareto point analysis in terms of capacity and generation. The top left shows the Pareto front of efficient solutions for the German power system in 2030 relative to the cost optimal solution P1. Here the ordinate shows the cost relative to a cost optimal system and the abscissa the impact also relative to a cost optimal system. Every point (P1–P11) of the front represents a non-dominated power system. The other three facets each depict the corresponding capacity on the right and the generation mix on the left for the modeling period λ of the three analyzed Pareto points. P1 (top right) represents the cost optimal, P11 (bottom left) the LCA based impact optimal and P10 (bottom right) the selected system.

the conventional power plants into the role of peak load generation. Consequently, the base load generation of lignite and coal in P1 is replaced by volatile wind and solar PV and a flexible commitment of biogas and natural gas in P11.

Figure 3 shows the temporally differentiated LCA dimension, again decomposed in a variable portion associated with the generation of electricity, and a fixed portion caused mainly through the capacity expansion. A very pronounced effect is visible concerning the fixed LCA-based impact. The low impact system of P10 shows a six-fold surge, which increases to even ten times the fixed impact in P11. The installation of wind and solar PV is the main driver for this development. Simultaneously, the variable impact is characterized by a massive decrease from P1–P10, mainly caused by the phase-out of lignite and coal. P11 only yields comparably small variable impact mitigation by restricting coal production to times with a very low wind generation. Essentially, the lower remaining impact associated with electricity is shifted from the generation to the production of the generation infrastructure. This trend is reflected when comparing the ratio of fixed to variable impact. In the cost optimal system the fixed impact is only 0.46% of the variable impact. This number rises to already 14.27% for P10 and 44.71% for P11.

This means, the generation of electricity causes mainly direct impacts in a cost-optimal system, for example, the combustion of fossil fuels, whilst the share of the impact caused by the production and construction of the power plants itself increases considerably in an LCA-based impact optimal system.

Contribution analyses

Constructing the modified technology matrix *A* and intervention matrices *B* facilitates the assessment of the effects of an optimized energy system on all products and processes of the global economy. Therefore, insights of the effect of a changing power supply on key industrial products and consumer goods is possible. The most pronounced effect however is expected for one unit of electricity itself, we therefore exemplary assess the environmental impacts of 1 kWh of German household level electricity for the three Pareto points and compare them to the corresponding impacts of the original ecoinvent 3.2 model (SI folder results 'H_elctr_low_voltage_market_DE_original, _p01, _p10, _p11'). The approach of the ReCiPe method to model the effect of emissions on 17 so called midpoint indicators enables the details analysis of the three systems regarding their respective performance.

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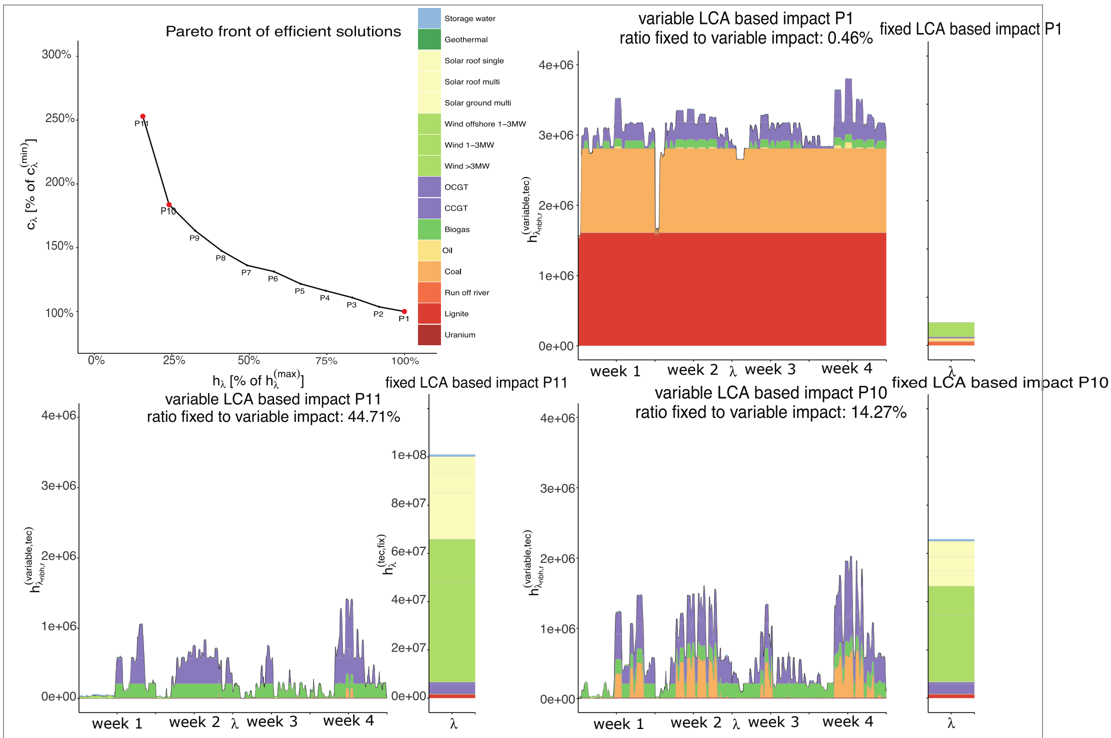

Figure 3. Pareto point analysis in terms of fixed and variable LCA-based impact. The top left shows the Pareto front of efficient solutions for the German power system in 2030 relative to the cost optimal solution P1. The other three facets each depict the corresponding fixed LCA-based impact on the right and the variable LCA-based impact on the left for the modeling period λ of the three analyzed Pareto points. P1 (top right) represents the cost optimal, P11 (bottom left) the LCA based impact optimal and P10 (bottom right) the selected system.

Figure 4 illustrates the performance concerning the 17 ReCiPe midpoint impact categories of the three Pareto points relative to the original data set (SI folder results ‘categorical_analysis’). Noticeable is the very similar total impact and impact distribution of P1 compared to the original data. The total impact of the low impact system on the other hand is reduced to only 34%. Furthermore, the categorical distributions of the impacts vary significantly compared to the original process, representing co-benefits and burdens. Most categories show a reduction, however, there are a few categories with a significantly higher impact, namely terrestrial ecotoxicity, metal depletion, agricultural land occupation, photochemical oxidant formation, and urban land occupation.

The observed shift from direct to indirect emissions as well as the considerable changes in a variety of impact categories highlights the relevance of a spatial contribution analysis to understand possible spatial redistribution implications. There are efforts to develop spatially differentiated impact assessment methods (Mutel *et al* 2012, de Baan *et al* 2013, Verones *et al* 2016). However, we use the global generic approach of the ReCiPe method since very specific complementary modeling approaches are necessary, which is beyond the scope of this paper (disregarding geographic variations in sensitivities to environmental pressure, and long-range transport of emission).

Figure 5 shows the results of the spatial contribution analysis for the total ReCiPe score and the seven most influential impact categories in terms of their contribution to the total impact (SI folder results ‘spatial_contribution_analysis’). The spatial distribution of the impact for every country is plotted for the original ecoinvent 3.2 process of 1 kWh of household level electricity relative to the overall intercategorical impact in figure 5(*a*). The impact of the total of the categories, fossil depletion, climate change, human health, and climate change ecosystems show a similar spatial distribution pattern. The majority is caused in Germany (53% for total), with France (6%), the United States (5%), Russia and China (3%) also facing a considerable amount of impacts. The agricultural land occupation map indicates a strong concentration of the impacts in Germany (24%) and even greater so in Sweden (59%, wood chips export). Human toxicity and metal depletion, on the other hand, are mainly attributed to the United States (24%) and China (15%) with only a small contribution in Germany (5%, 3%). Particulate matter is characterized by an expected concentration of the impacts in Germany with a share of 54%.

Highlighting the changes, which come with the low impact system P10, the relative changes compared to the original database are plotted in figure 5(*b*). Here the intercategorical spatial redistribution effects are

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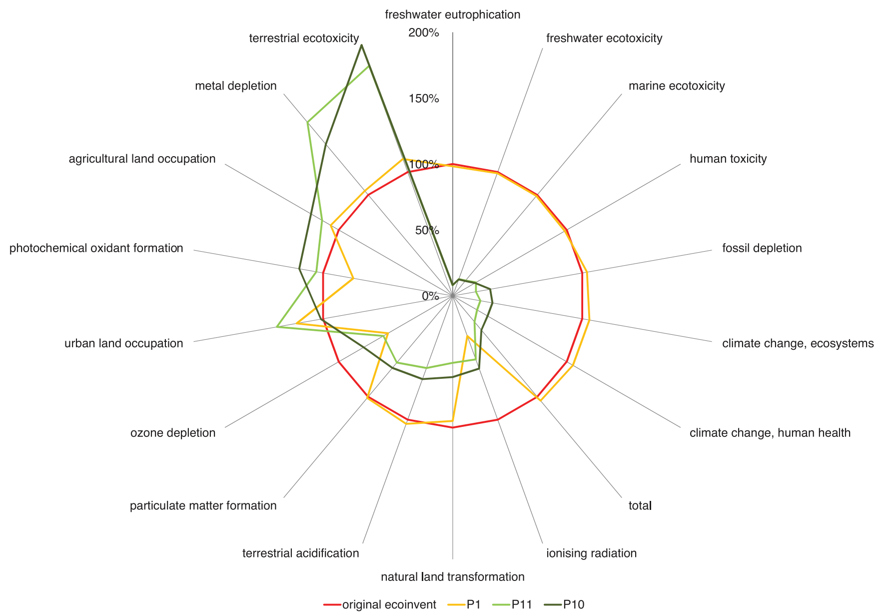

Figure 4. Categorical analysis of the process 'DE market for electricity, low voltage'. The three Pareto points chosen for the in-depth analysis are evaluated in terms of their performance concerning the 17 ReCiPe H/A midpoint impact categories. The impacts are plotted relative to those of the original ecoinvent 3.2 process.

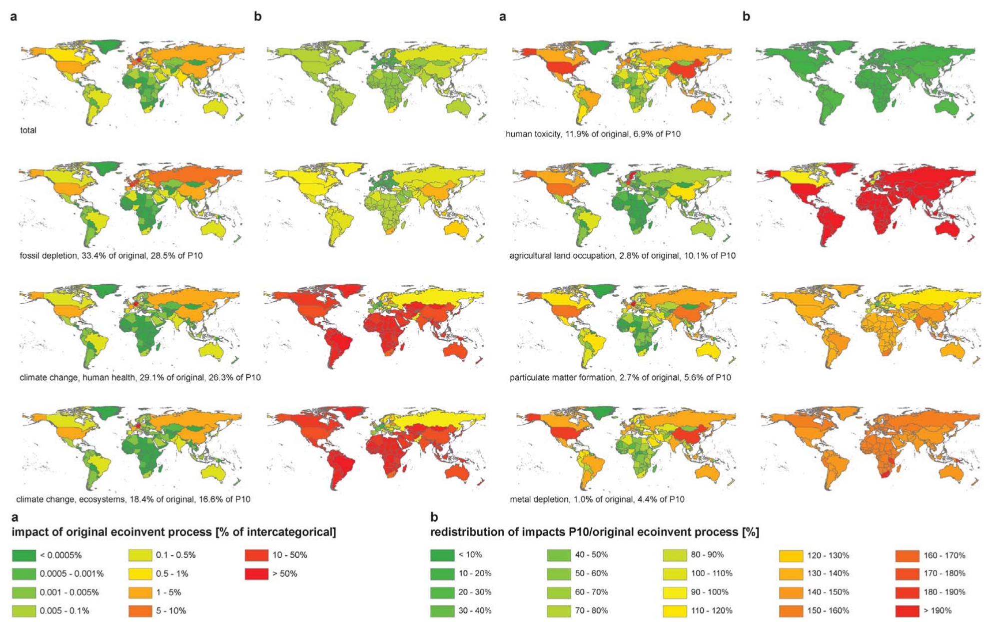

Figure 5. Spatial contribution analysis of the process 'DE market for electricity, low voltage'. The figure illustrates the spatial distribution of the total ReCiPe indicator and the seven midpoint categories of the original ecoinvent 3.2 process in (*a*). The midpoints categories are selected according to their relative contribution to the total impact, given in each caption. (*b*) Shows the redistribution effect for the same impact categories as a relative change from the original ecoinvent 3.2 to the P10 process.

examined. The shift from variable to fixed impacts already seen in the ESM is also prominent in the adjusted corresponding LCA database processes of P10. All eight indicators show a moderate to significant decrease of the impact in Europe and Germany especially. The absolute distribution of the total impact is shifting to only 31% (53% original) in Germany, 11% (5%) in the United States, 9% (3%) in Russia and 8% (3%) in China. As stated above the main cause is the redistribution of the impacts upstream on the supply chain. The analysis of the other world regions reveals the impact of this shift. Despite the decrease of the total

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impact in all countries, the heterogeneous redistribution mainly affects particulate matter formation, metal depletion, and agricultural land occupation. A very prominent example is particulate matter: the United States (16%) and China (14%) are almost experiencing the same impact as Germany (18%). The climate change categories redistribution effects indicate the increased GHG emissions outside of Germany for the production of power infrastructure.

Discussion

This study is the first analysis developing a hybrid modeling framework combining a multi-objective ESM with LCA answering the call for collaboration of the energy system modeling and the industrial ecology communities. Furthermore, the approximation of the whole spectrum of efficient solutions and the integration of a LCA database enables the decision maker to make truly informed decisions when designing policies, taking into account a wide array of emission and corresponding response functions. The encompassing nature of the method provides information about a comprehensive set of co-benefits and burdens identifying possible areas of conflict between a sustainability driven power supply and single impact categories. However, achieving completeness requires a generic impact assessment, the detailed assessment of these co-benefits and burdens each should be addressed with a more specific modeling approach.

MOrOSA includes the whole supply chain of the modeled technologies, achieved through the integration of a non-monetized elaborated LCA-based framework for sustainability. The separate modeling of capacity and generation provides a detailed assessment of the Pareto points, both in terms of the fixed impact associated with the power infrastructure and variable impact associated with the generation of electricity itself. This facilitates the analysis of spatial impact leakage up the supply chain. A feature highly relevant for policy advice when considering that only about 56% (original ecoinvent 3.2) of the impacts according to ReCiPe score are caused in Germany, this share even drops to 31% for the analyzed low impact system of P10. Besides that, the drastic increase of the impact caused by the power supply infrastructure compared to the actual burning of fuels highlights the relevance of the consideration of the whole supply chain accounting for embodied emissions. Another key insight is provided by the feedback of the ESM into the LCA database, facilitating the in-depth analysis of the implications of changing power systems on all processes and products of the economy. This is especially relevant for designing policies considering that every economic branch uses electricity as an input. The feedback also enables contribution analyses according to unit processes by providing a holistic picture of important processes and/or regions. The exemplary assessment of 1 kWh of electricity in Germany shows that besides the decrease of the total impact, there are other impact categories where the allegedly sustainable scenarios show a high increase in impact (metal depletion, agricultural land occupation). Additionally, the spatial contribution analysis differentiates this finding and illustrates which spatial implications arise due to an electricity system based on renewable energies. Although the overall ReCiPe impact score decreases in all countries, the analysis reveals the prevailing trend of certain environmental impacts shifting from Germany upstream the supply chain to the countries of production of the power generation technologies.

The combination of multi-objective energy system modeling and LCA has still a number of shortcomings. Generally, hybrid modeling does not provide full consistency (Haes *et al* 2004). The classification of processes in ecoinvent 3.2, relevant for the German energy system, is not identical to the classification in the ESM. To overcome this, we selected representative processes to determine the impacts of its variable and fixed parts impacts as input flow for the ESM. Respectively, it is necessary to split the aggregated structure of the ESM into the more detailed structure of ecoinvent 3.2. Hence, future effort is necessary to adjust the ESM technology classification to the LCI database. Additionally, the aim of future research should be to improve LCA databases by providing spatially differentiated processes as well as impact characterization factors. Another important issue is the process of updating the ecoinvent 3.2 databases according to the optimization. In the current version of the hybrid model, the LCA database is modified at the end of the optimization. The dynamic adoption of upstream effects due to a modified electricity system is not considered. Hence, future research should analyze to what extent a more frequent modification of the LCI database is preferable. The main issue here is the necessary inversion of the high dimensional technology matrix A, which will considerably increase computation time. Social aspects are so far only considered in the form of human health. However, there is the possibility to broaden the scope by introducing a third objective function using a social intervention matrix in the same manner as the environmental intervention matrix in LCA. Although there are recent efforts in the LCA community concerning the development of such databases, the current data availability is not suitable for inclusion in this study. Additionally, this study uses the cut-off model of the ecoinvent 3.2 database. There are other models differing in how they deal with multi-functional processes. The cut-off model always allocates primary production of to the primary user of a material. Future studies should check how upstream impacts change due to this modelling choice and to what extend results are affected. A potential alternative to LCA databases is the coupling of ESM with a multi-regional environmentally extended input-output database. Those databases can illustrate the interrelations of sectors between

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different regions in a more consistent manner. On the other hand, environmental interventions are less comprehensive compared to LCA databases. Combining both models and integrating them into ESM should therefore be another field of future research.

Conclusion

The application of the developed modelling approach to the case study of the German power system expansion problem revealed a variety of insights. Most prominently, the inclusion of the LCA based sustainability consideration into the optimization showed the cost efficient achievement of impact mitigation in the power sector: reducing the impact by a factor of four with a moderate increase in cost. Additionally, these results are in line with climate mitigation scenarios, showing the sustainability benefits of renewable power generation not only for the climate but on many environmental dimensions. The integrated assessment of energy system futures and their effect on sustainability is expected to gain relevance through projected developments in the energy system: for example the electrification of transport, heat and other sectors, global supply chains, and the decarbonization of the energy system of world regions with different speeds. Here trade-offs are often not obvious and informed decisions require an integrated assessment. This study should therefore be seen as a first step towards an integrated assessment strengthening the call for joint work of the energy system and industrial ecology communities on these issues.

Author contributions

S R led the overall effort and wrote most of the paper. M B contributed formulating the theoretical LCA chapters, carrying out the contribution analyses, and formulating the discussion. Both authors developed the general structure of the hybrid modeling.

Appendix A: Energy system modeling

The main parameters are the modeling period λ, the modeled hours λ_{nbh}, the region r, the power plant number n and the technology type tec. The objective function is to minimize the total system cost c for the modeling period, see equation A.1. Selected constraints are illustrated by equations A.2–A.8. They include the supply and demand, the maximal and minimal capacity, part-load efficiency and the shut-down and start-up constraints (SI ESM folder 'MOrOSA_core_GAMS_code').

$$\begin{aligned} &\text{Minimize } f_{\text{economic}}(x) = c_{\lambda} \\ &= c_{\lambda}^{\text{variable}} + c_{\lambda}^{\text{fuel}} + c_{\lambda}^{\text{tax}} + c_{\lambda}^{\text{fix}} + c_{\lambda}^{\text{transmission}} \\ &+ c_{\lambda}^{\text{import-export}} + c_{\lambda}^{CO_2} + c_{\lambda}^{\text{ramping}} + c_{\lambda}^{\text{start-up}} \\ &+ c_{\lambda}^{\text{storage-water-pump}} + c_{\lambda}^{\text{part-load-penalty}} \end{aligned} \tag{A.1}$$

subject to

$$p_{\lambda_{\text{nhb}},\text{r}}^{\text{residual}} \sum_{v=1}^{n} p_{\lambda_{\text{nbh}},\text{r,n}}^{\text{com.eff}} + p_{\lambda_{\text{nbh}},\text{r}}^{\text{transm.diff.}} \tag{A.2}$$

$$\begin{aligned} &p_{\lambda_{\text{nbh}},\text{r}}^{\text{transmission difference}} \sum_{w=1}^{line} p_{\lambda_{\text{nbh}},\text{line}}^{\text{transm.import}} \\ &- \sum_{w=1}^{\text{line}} p_{\lambda_{\text{nbh}},\text{line}}^{\text{transm.export}} \end{aligned} \tag{A.3}$$

$$\chi_{\lambda_{\text{nbh}},n}^{\text{start-up}} - \chi_{\lambda_{\text{nbh}},n}^{\text{shut-down}} = \chi_{\lambda_{\text{nbh}},n}^{\text{com.}} - \chi_{\lambda_{\text{nbh}}-1,n}^{\text{com.}} \tag{A.4}$$

$$\chi_{\lambda_{\text{nbh}},n}^{\text{com.}} + (1 - \chi_{\lambda_{\text{nbh}}-1,n}^{\text{com.}}) = 1 \tag{A.5}$$

$$p_{\lambda_{\text{nbh}},n}^{\text{com.}} \leq u_n p_n^{\text{block size}} \chi_{\lambda_{\text{nbh}},n}^{\text{com.}} \tag{A.6}$$

$$p_{\lambda_{\text{nbh}},n}^{\text{com.}} \geq u_n p_n^{\text{min.com.}} \chi_{\lambda_{\text{nbh}},n}^{\text{com.}} \tag{A.7}$$

$$\begin{aligned} p_{\lambda_{\text{nbh}},r,n}^{\text{com.}_{\text{eff}}} &= p_{\lambda_{\text{nbh}}-1,r,n}^{\text{com.}_{\text{eff}}} + p_{\lambda_{\text{nbh}},n}^{\text{ramp-up}} + \chi_{\lambda_{\text{nbh}},n}^{\text{start-up}} \\ &\quad p_n^{\text{min.com.}} - p_{\lambda_{\text{nbh}},n}^{\text{ramp-down}} - \chi_{\lambda_{\text{nbh}},n}^{\text{shut-down}} p_n^{\text{min.com.}}. \end{aligned} \tag{A.8}$$

The possibility to invest and disinvest is implemented by the introduction of binary variables described by equations (A.9) and (A.10)

$$\sum_{q=1}^{\lambda_{\text{nbh}}} \chi_{\lambda_{\text{nbh}},n_{\text{exist}}}^{\text{decom.}} + \varepsilon \geq \sum_{q=1}^{\lambda_{\text{nbh}}} \chi_{\lambda_{\text{nbh}},n_{\text{exist}}}^{\text{com.}} \tag{A.9}$$

$$\sum_{q=1}^{\lambda_{\text{nbh}}} \chi_{\lambda_{\text{nbh}},n_{\text{pot.}}}^{\text{built}} + \varepsilon \leq \sum_{q=1}^{\lambda_{\text{nbh}}} \chi_{\lambda_{\text{nbh}},n_{\text{pot.}}}^{\text{com.}} \tag{A.10}$$

The resulting fixed costs equation depends on the investment or disinvestment of capacity and consists of quasi-fixed and annualized capital cost related to the power plant capacity (equation A.11)

$$\begin{aligned} c_{\lambda}^{\text{fix}} = &\sum_{v=1}^{n_{\text{exist}}} \chi_{\lambda_{\text{nhb}},n_{\text{exist}}}^{\text{decom.}} p_{n_{\text{exist}}}^{\text{capacity}} \times \\ &\left(c_{n_{\text{exist}}}^{\text{quasi fix}} + c_{n_{\text{exist}}}^{\text{invest fix}} \frac{(1+d)^{\alpha n_{\text{exist}} * d})}{(1+d)^{\alpha n_{\text{exist}}} - 1} \right) \frac{8760h}{\lambda_{\text{nbh}}} + \\ &\sum_{v=1}^{n_{\text{pot.}}} \chi_{\lambda_{\text{nbh}},n_{\text{pot.}}}^{\text{built}} p_{n_{\text{pot.}}}^{\text{capacity}} \times \\ &\left(c_{n_{\text{pot.}}}^{\text{quasi fix}} + c_{n_{\text{pot.}}}^{\text{invest fix}} \frac{(1+d)^{\alpha n_{\text{pot}},*d}}{(1+d)^{\alpha n_{\text{pot.}}-1}} \right) \\ &\frac{8760h.}{\lambda_{nbh}} \end{aligned} \tag{A.11}$$

The introduction of the possibility to invest and disinvest in capacity requires the simplification of the model to be solvable in a reasonable time. Clustering is an effective way to improve the computational burden while limiting the loss of detail (Palmintier and Webster 2011). The model considers the fuel efficiency rate as a function of the technology type and the commission year. Therefore, the clustering is performed along these features.

Introducing the LCA dimension extends the original optimization problem to a multi-objective one represented by the formulation of equation (A.12)

$$\begin{aligned}&\text{minimize } (f_{\text{economic}}(x), f_{\text{LCA}}(x))\\&\text{subject to}\\&x \in S\end{aligned} \tag{A.12}$$

where $f_{\text{economic}}(x)$ and $f_{\text{LCA}}(x)$ are the objective functions, x the decision variables vector and S the feasible region in the solution space. $f_{\text{LCA}}(x)$ consists of a variable and a fixed share defined by equations (A.13–A.15). The fixed impacts are distributed over the depreciation period of the power plant

$$f_{\text{LCA}}(x) = h_\lambda = h_\lambda^{\text{variable}} + h_\lambda^{\text{fix}} \tag{A.13}$$

$$h_\lambda^{\text{variable}} = \sum_{q=1}^{\lambda_{\text{nbh}}} \sum_{j=v}^{n} p_{\lambda_{\text{nbh},n}}^{\text{com.}} h_{\text{tec}}^{\text{variable}} \frac{1}{\eta_{n,\phi}} | n \in \text{tec} \tag{A.14}$$

$$\begin{aligned}h_\lambda^{\text{fix}} = &\sum_{v=1}^{n_{\text{exist}}} \chi_{\lambda_{\text{nbh}}, n_{\text{exist.}}}^{\text{decom.}} p_{n_{\text{exist}}}^{\text{capacity}} h_{\text{tec}}^{\text{fix}} \frac{\lambda_{\text{nbh}}}{8760h} \frac{1}{\alpha_{n_{\text{exist.}}}}\\&+ \sum_{v=1}^{n_{\text{pot.}}} \chi_{\lambda_{\text{nbh}}, n_{\text{pot.}}}^{\text{built}} p_{n_{\text{pot.}}}^{\text{capacity}} h_{n_{\text{pot.}}}^{\text{fix}} \frac{\lambda_{\text{nbh}}}{8760h} \frac{1}{\alpha_{n_{\text{pot.}}}}\\&| \alpha_{n_{\text{exist}}}, \alpha_{n_{\text{pot.}}} \lambda-,\ n \in \text{tec}.\end{aligned} \tag{A.15}$$

There are two methods that are mainly used to generate the Pareto front, the weighting, and the ε-constraint method (Mavrotas 2009). The weighting method is the most intuitive, as it finds the supported solutions through a convex combination of the objective functions. This, however, yields some disadvantages. Among them the inability to obtain unsupported solutions, the sensitivity to scaling and the difficulty in setting the number of calculated grid points. The ε-constraint method does not face these disadvantages and the inherent drawbacks can be dealt with through the development of an augmented version (Mavrotas and Florios 2013b). The general idea is to optimize a primary objective function while expressing the other objective functions as inequality constraints, leading to equation (A.16)

$$\begin{aligned}&\text{minimize } f_{\text{economic}}(x)\\&\text{subject to}\\&f_{\text{LCA}}(x)\varepsilon\\&x \in S.\end{aligned} \tag{A.16}$$

The ε-constraint method was applied to a variety of energy-related problems, among them the electricity market clearing (Aghaei and Amjady 2012), the expansion planning of the transmission grid (Maval-izadeh and Ahmadi 2014) and portfolio management (Esmaeel Nezhad *et al* 2015). The algorithm applied in this study is an adapted version of the augmented ε-constraint algorithm (Mavrotas 2009, Mavrotas and Florios 2013a). The general process is to calculate the payoff table through lexicographic optimization, determining the nadir and utopia point. The range of the second objective function is then divided into intervals and corresponding grid points. These are iteratively used to adjust the ε of equation (A.16) while optimizing, f_{economic} generating the Pareto front. The advantages over the standard ε-constraint method are that grid points not providing Pareto optimal solutions are skipped. Additionally, the conversion of the inequalities to equalities through the introduction of slack variables ensures that only strict non-dominated solutions are calculated (Mavrotas and Florios 2013b).

Appendix B: Life cycle assessment

Life cycle impact assessment converts the environmental inputs and outputs into indicator results of categories that are better understandable in terms of environmental significance. In matrix notation, the potential environmental impact vector h_l results from multiplying the matrix of characterization factors $Q_{l,k}$, the intervention matrix $B_{k,j}$ (process specific environmental inputs and outputs), the inverse of the technology matrix $A_{j,i}$ (representing the linkage between the processes) and the final demand vector f_i that specifies the functional unit, expressed through equation (B.1). Where k is the environmental intervention, l the impact category, i the technology matrix flow and j the process (Heijungs and Suh 2002)

$$h_l = Q_{l,k} B_{k,j} A_{i,j}^{-1} f_i. \tag{B.1}$$

Several databases provide LCI data for A and B matrices. Additionally, a variety of life cycle impact assessment methodologies exists that provide the characterization factors of Q. In this study, LCI data of the ecoinvent 3.2 cut-off system model and the characterization factors of the ReCiPe methodology are used. This methodology provides characterization factors considering the significance of the indicator results of 17 midpoint impact categories. These are aggregated into three endpoint impact categories: damage to human health [disability-adjusted loss of life years], to ecosystem diversity [loss of species during a year] and to resource availability [increased cost]. The quantification of a single score using the hierarchist perspective enables the optimization of the German electricity system in terms of several weighted impact categories. This weighting in terms of societal preferences is subject to debate and adjustments according to decision maker preferences are possible.

As input, the optimization algorithm of the energy system model requires the environmental impacts of variable and fixed parts of each generation technology determined by equation (B.2)

$$h_{l,n} = Q_{l,k} B_{k,j} A_{j,i}^{-1} f_n | n \in \text{tec}. \tag{B.2}$$

Equation (B.3) calculates the indicator result of variable parts of the electricity system, such as fuel,

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related to 1 kWh electricity output of the corresponding technology. The demand vector for the variable part of the impact is calculated by subtracting the fixed share, such as construction material, from the functional unit that represents the overall generation of 1 kWh electricity of the corresponding technology (SI LCA folder 'h_variable')

$$h^{\text{variable}}_{l,\text{tec}} = Q_{l,k} B_{k,j} A^{-1}_{j,i} (f_{\text{tec},i} - f_{\text{tec,fixed}_{\text{share}}}). \quad \text{(B.3)}$$

Matching the fixed part of the ESM which is represented in units of capacity requires the indicator result to be divided by the size of the installed capacity (see equation (B.4)) (SI LCA folder 'h_fixed_kW')

$$h^{\text{fixed}}_{l,\text{tec}} = \frac{Q_{l,k} B_{k,j} A^{-1}_{j,i} f_{\text{tec,fixed\_unit}}}{p^{\text{block size}}_{i}}. \quad \text{(B.4)}$$

The result of the optimization algorithm is a Pareto front of optimal solutions in terms of costs and environmental impacts. Assessing these optimal solutions with the full capabilities of the LCA is achieved through the feedback of the ESM results into the LCA database. Therefore, a new LCA database is created using the updated and optimized electricity processes. For each of them a new process vectors P^* is formulated to take into consideration technology and commissioning year specific characteristics, according to equation (B.5). These vectors include the new data of the optimization model for the technology matrix A^* and the intervention matrix B^*

$$p^{*}_{\text{tec}} = \begin{pmatrix} a^{*}_{i,j} \\ \hline b^{*}_{k,j} \end{pmatrix} = \begin{pmatrix} a_{\text{var}_{i,j}} \Delta\eta_{\text{tec},\phi} \\ a_{\text{fix}_{i,j}} \\ \hline b_{k,j} \Delta\eta_{\text{tec},\phi} \end{pmatrix} \mid j \in \text{tec}. \quad \text{(B.5)}$$

The change of efficiency rates incorporated in the efficiency rate vector $\Delta_{\eta n}$ are applied to the variable interventions b and the variable part of the technology vector a. $\Delta_{\eta n}$ is calculated throught the tec specific generation weighted difference of the commission date dependent efficiency compared to the base year efficiency. By the use of the adopted database, comprehensive analyses of the environmental impacts related to the changing German electricity system are possible.

The last phase of LCA, interpretation, deals with the meaning and the robustness of the results. An important aspect in terms of interpreting the meaning of results is the contribution analysis (Heijungs and Suh 2002). Thereby, for example, the contribution of unit processes to the overall impact indicator result can be determined according to equation (B.6). The set of unit processes P is partitioned according to i

$$\begin{aligned} s_j &= A^{-1}_{j,i} f_i \\ \forall l : h_l(P_i) &= S^{T}_{j} \circ (Q_{l,k} B_{k,j}) | j \in P_i. \end{aligned} \quad \text{(B.6)}$$

Now it is possible to summarize $h_1(P_a)$ over different impact categories as well as geographic locations. The ecoinvent 3.2 database assigns a spatial location to all processes in the A matrix. Despite the majority of these spatial allocations being country or subcountry level, there are processes with a superordinate location assignment. To allocate these impacts to countries the relative economic performance based on gross domestic products (GDP) for the year 2015 (The World Bank 2017) is used.

Appendix C: Case study data and assumptions

The 2015 power system functions as the originator for the optimization. The input data encompasses the available generation capacity at the power plant level (Rauner *et al* 2016), the demand data of electricity (European Network of Transmission System Operators for Electricity 2016) as well as the capacity factors of RES-E (Staffell and Pfenninger 2016, Pfenninger and Staffell 2016) (SI folder ESM). Also included are the power plant data, in most cases a function of the commission year φ and the type of technology *tec* (Schröder *et al* 2013), the fuel price of conventional technologies (Kost *et al* 2013) which is assumed to be stable over the modeled period, and the efficiency data of conventional technologies (Schröder *et al* 2013). Similarly, the trend in recent years suggests the assumption of a stable load development is reasonable, despite other political goals. Additionally, the depreciation period α is an important parameter (Schröder *et al* 2013). The efficiency of RES-E technologies is also assumed to stable. The model is able to disinvest when the lifetime is reached with a period of five years after which the power plant has to be mandatorily disinvested. The bioenergy technology is assumed to be heat driven until 2015, plants with a later commissioning date are capable of flexible generation. The current wind power is assumed to fall in the ecoinvent 3.2 category of 1–3 MW turbines whilst the potential plants fall into the >3 MW category. Refer to SI folder LCA for the variable, associated with the generation of electricity, and fixed, power system infrastructure, s, g (inventory vector *Bs*) and h matrices of all *tec*. The extension of the RES-E technologies is restricted to 200% of the governmental goal until 2030. Load shedding is possible with assigned cost of 1000€ MWh^{-1}. The storage water capacity is assumed exhausted already in the base year. Fuel tax of the base year and a CO_2 price is set to 8€ t^{-1}.

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References

Aghaei J and Amjady N 2012 A scenario-based multiobjective operation of electricity markets enhancing transient stability *Int. J. Electr. Power Energy Syst.* **35** 112–22

Atilgan B and Azapagic A 2016 An integrated life cycle sustainability assessment of electricity generation in Turkey *Energy Policy* **93** 168–86

Azapagic A 1999 Life cycle assessment and its application to process selection, design and optimisation *Chem. Eng. J.* **73** 1–21

Azapagic A and Clift R 1999 Life cycle assessment and multiobjective optimisation *J. Clean. Prod.* **7** 135–43

de Baan L, Mutel C L, Curran M, Hellweg S and Koellner T 2013 Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction *Environ. Sci. Technol.* **47** 9281–90

Barteczko-Hibbert C, Bonis I, Binns M, Theodoropoulos C and Azapagic A 2014 A multi-period mixed-integer linear optimisation of future electricity supply considering life cycle costs and environmental impacts *Appl. Energy* **133** 317–34

Berrill P, Arvesen A, Scholz Y, Gils H C and Hertwich E G 2016 Environmental impacts of high penetration renewable energy scenarios for Europe *Environ. Res. Lett.* **11** 014012

Buoro D, Casisi M, De Nardi A, Pinamonti P and Reini M 2013 Multicriteria optimization of a distributed energy supply system for an industrial area *Energy* **58** 128–37

Daly H E, Scott K, Strachan N and Barrett J 2015 Indirect CO_2 emission implications of energy system pathways: linking IO and TIMES models for the UK *Environ. Sci. Technol.* **49** 10701–9

Ekvall T, Assefa G, Björklund A, Eriksson O and Finnveden G 2007 What life-cycle assessment does and does not do in assessments of waste management *Waste Manage.* **27** 989–96

Esmaeel Nezhad A, Ahmadi A, Javadi M S and Janghorbani M 2015 Multi-objective decision-making framework for an electricity retailer in energy markets using lexicographic optimization and augmented epsilon-constraint *Int. Trans. Electr. Energy Syst.* **25** 3660–80

European Commission 2011 *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions* (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0885&from=EN)

European Network of Transmission System Operators for Electricity 2016 entsoe Transparancy Platform (https://transparency.entsoe.eu/)

Fazlollahi S, Mandel P, Becker G and Maréchal F 2012 Methods for multi-objective investment and operating optimization of complex energy systems *Energy* **45** 12–22

Flores-Quiroz A, Palma-Behnke R, Zakeri G and Moreno R 2016 A column generation approach for solving generation expansion planning problems with high renewable energy penetration *Electr. Power Syst. Res.* **136** 232–41

Gasparatos A, Doll C N H, Esteban M, Ahmed A and Olang T A 2017 Renewable energy and biodiversity: implications for transitioning to a green economy *Renew. Sustain. Energy Rev.* **70** 161–84

Gebreslassie B H, Guillén-Gosálbez G, Jiménez L and Boer D 2009 Design of environmentally conscious absorption cooling systems via multi-objective optimization and life cycle assessment *Appl. Energy* **86** 1712–22

Gerber L, Gassner M and Maréchal F 2011 Systematic integration of LCA in process systems design: application to combined fuel and electricity production from lignocellulosic biomass *Comput. Chem. Eng.* **35** 1265–80

Gibon T, Hertwich E G, Arvesen A, Singh B and Verones F 2017 Health benefits, ecological threats of low-carbon electricity *Environ. Res. Lett.* **12** 034023

Gibon T, Wood R, Arvesen A, Bergesen J D, Suh S and Hertwich E G 2015 A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change *Environ. Sci. Technol.* **49** 11218–26

Goedkoop M and Huijbregts M 2013 ReCiPe 2008

Gujba H, Mulugetta Y and Azapagic A 2011 Power generation scenarios for Nigeria: an environmental and cost assessment *Energy Policy* **39** 968–80

Haes H A U, Heijungs R, Suh S and Huppes G 2004 Three strategies to overcome the limitations of life-cycle assessment *J. Ind. Ecol.* **8** 19–32

Heijungs R and Suh S 2002 *The Computational Structure of Life Cycle Assessment* vol 11 (Dordrecht: Springer Netherlands)

Heinrich G, Basson L, Howells M and Petrie J 2007 Ranking and selection of power expansion alternatives for multiple objectives under uncertainty *Energy* **32** 2350–69

Hertwich E G, Gibon T, Bouman E A, Arvesen A, Suh S, Heath G A, Bergesen J D, Ramirez A, Vega M I and Shi L 2015 Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies *Proc. Natl Acad. Sci.* **112** 6277–82

Howells M *et al* 2013 Integrated analysis of climate change, land-use, energy and water strategies *Nat. Clim. Change* **3** 621–6

Hwang C-L and Masud A S M 1979 *Multiple Objective Decision Making — Methods and Applications* vol 164 (Berlin: Springer)

Ingle N A and Lakade S S 2016 Design and development of downdraft gasifier to generate producer gas *Energy Procedia* **90** 423–31

Intergovernmental Panel on Climate Change 2014 *Climate Change 2014—Mitigation of Climate Change* (Cambridge: Cambridge University Press)

Kamalinia S, Shahidehpour M and Khodaei A 2011 Security-constrained expansion planning of fast-response units for wind integration *Electr. Power Syst. Res.* **81** 107–16

Karger C R and Hennings W 2009 Sustainability evaluation of decentralized electricity generation *Renew. Sustain. Energy Rev.* **13** 583–93

Kim S-H 2007 Evaluation of negative environmental impacts of electricity generation: neoclassical and institutional approaches *Energy Policy* **35** 413–23

Kost C, Mayer J N, Thomsen J, Hartmann N, Senkpiel C, Philipps S, Nold S, Lude S, Saad N and Schlegel T 2013 Levelized cost of electricity renewable energy technologies (www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf)

Kouloumpis V, Stamford L and Azapagic A 2015 Decarbonising electricity supply: is climate change mitigation going to be carried out at the expense of other environmental impacts? *Sustain. Prod. Consum.* **1** 1–21

Kowalski K, Stagl S, Madlener R and Omann I 2009 Sustainable energy futures: methodological challenges in combining scenarios and participatory multi-criteria analysis *Eur. J. Oper. Res.* **197** 1063–74

Laurent A and Espinosa N 2015 Environmental impacts of electricity generation at global, regional and national scales in 1980-2011: what can we learn for future energy planning? *Energy Environ. Sci.* **8** 689–701

Lelieveld J, Evans J S, Fnais M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale *Nature* **525** 367–71

Liu J *et al* 2015 Systems integration for global sustainability *Science* **347** 1258832

Ma J, Silva V, Belhomme R, Kirschen D S and Ochoa L F 2013 Evaluating and planning flexibility in sustainable power systems *IEEE Trans. Sustain. Energy* **4** 200–9

Mavalizadeh H and Ahmadi A 2014 Hybrid expansion planning considering security and emission by augmented epsilon-constraint method *Int. J. Electr. Power Energy Syst.* **61** 90–100

Mavrotas G 2009 Effective implementation of the ε-constraint method in multi-objective mathematical programming problems *Appl. Math. Comput.* **213** 455–65

Mavrotas G, Diakoulaki D, Florios K and Georgiou P 2008 A mathematical programming framework for energy planning in services' sector buildings under uncertainty in load demand: the case of a hospital in Athens *Energy Policy* **36** 2415–29

IOP Publishing Environ. Res. Lett. 12 (2017) 124005 Letters

Mavrotas G and Florios K 2013a An improved version of the augmented ε-constraint method (AUGMECON2) for finding the exact pareto set in multi-objective integer programming problems *Appl. Math. Comput.* **219** 9652–69

Meyerhoff J, Ohl C and Hartje V 2010 Landscape externalities from onshore wind power *Energy Policy* **38** 82–92

Mutel C L, Pfister S and Hellweg S 2012 GIS-based regionalized life cycle assessment: how big is small enough? Methodology and case study of electricity generation *Environ. Sci. Technol.* **46** 1096–103

Newlands N K 2016 *Future Sustainable Ecosystems: Complexity, Risk, and Uncertainty* (Boca Raton, FL: CRC Press)

Oliveira C and Antunes C H 2004 A multiple objective model to deal with economy-energy-environment interactions *Eur. J. Oper. Res.* **153** 370–85

Pachauri R K *et al* 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* (Cambridge: Cambridge University Press)

Palmintier B and Webster M 2011 Impact of unit commitment constraints on generation expansion planning with renewables *2011 IEEE Power and Energy Society General Meeting (Detroit, MI, 24–29 July 2011)* (https://doi.org/10.1109/PES.2011.6038963)

Pauliuk S, Arvesen A, Stadler K and Hertwich E G 2017 Industrial ecology in integrated assessment models *Nat. Clim. Change* **7** 13–20

Pfenninger S and Staffell I 2016 Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data *Energy* **114** 1251–65

Pieragostini C, Mussati M C and Aguirre P 2012 On process optimization considering LCA methodology *J. Environ. Manage.* **96** 43–54

Pina A, Silva C A and Ferrão P 2013 High-resolution modeling framework for planning electricity systems with high penetration of renewables *Appl. Energy* **112** 215–23

Rao S *et al* 2016 A multi-model assessment of the co-benefits of climate mitigation for global air quality *Environ. Res. Lett.* **11** 124013

Rauner S, Eichhorn M and Thrän D 2016 The spatial dimension of the power system: investigating hot spots of smart renewable power provision *Appl. Energy* **184** 1038–50

Rosen J, Tietze-Stöckinger I and Rentz O 2007 Model-based analysis of effects from large-scale wind power production *Energy* **32** 575–83

Santoyo-Castelazo E and Azapagic A 2014a Sustainability assessment of energy systems: integrating environmental, economic and social aspects *J. Clean. Prod.* **80** 119–38

Santoyo-Castelazo E and Azapagic A 2014b Sustainability assessment of energy systems: integrating environmental, economic and social aspects *J. Clean. Prod.* **80** 119–38

Schenler W, Hirschberg S, Burgherr P, Makowski M and Granat J 2009 *Final report on sustainability assessment of advanced electricity supply options* (www.psi.ch/ta/NeedsEN/RS2bD10.2.pdf)

Schröder A, Kunz F, Meiss J, Mendelevitch R, Von Hirschhausen C, Meiss J and Von Hirschhausen C 2013 Current and prospective costs of electricity generation until 2050 *Data Documentation 68* (www.diw.de)

Shmelev S E and van den Bergh J C J M 2016 Optimal diversity of renewable energy alternatives under multiple criteria: an application to the UK *Renew. Sustain. Energy Rev.* **60** 679–91

Söderholm P and Sundqvist T 2003 Pricing environmental externalities in the power sector: ethical limits and implications for social choice *Ecol. Econ.* **46** 333–50

Staffell I and Pfenninger S 2016 Using bias-corrected reanalysis to simulate current and future wind power output *Energy* **114** 1–34

Stamford L and Azapagic A 2012 Life cycle sustainability assessment of electricity options for the UK *Int. J. Energy Res.* **36** 1263–90

Sütő B, Könnyű Z, Tölgyesi Z, Skala T, Rudas I and Kozlovszky M 2015 3D human scanning solution for medical measurements *Technological Innovation for Cloud-Based Engineering Systems* vol **450** ed L M Camarinha-Matos, T A Baldissera, G Di Orio and F Marques (Cham: Springer)

The World Bank 2017 World Development Indicators (http://databank.worldbank.org)

Treyer K and Bauer C 2016 Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database? Part II: electricity markets *Int. J. Life Cycle Assess.* **21** 1255–68

Treyer K, Bauer C and Simons A 2014 Human health impacts in the life cycle of future European electricity generation *Energy Policy* **74** S31–44

Turconi R, Boldrin A and Astrup T 2013 Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations *Renew. Sustain. Energy Rev.* **28** 555–65

Nations United 2015 Transforming our world: the 2030 agenda for sustainable development *General Assembly 70th Session* **16301** 1–35

Varun, Bhat I K and Prakash R 2009 LCA of renewable energy for electricity generation systems—a review *Renew. Sustain. Energy Rev.* **13** 1067–73

Verones F, Hellweg S, Azevedo L B, Laurent A, Mutel C L and Pfister S 2016 A spatially differentiated life cycle impact assessment approach *LC-Impact Version 0.5 Report* (www.lc-impact.eu/downloads/documents/LC-Impact_report_SEPT2016_20160927.pdf)

West J J *et al* 2013 Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health *Nat. Clim. Change* **3** 885–9

Wiser R, Bolinger M, Heath G, Keyser D, Lantz E, Macknick J, Mai T and Millstein D 2016a Long-term implications of sustained wind power growth in the United States: potential benefits and secondary impacts *Appl. Energy* **179** 146–58

Wiser R, Millstein D, Mai T, Macknick J, Carpenter A, Cohen S, Cole W, Frew B and Heath G 2016b The environmental and public health benefits of achieving high penetrations of solar energy in the United States *Energy* **113** 472–86

World Energy Council 2016 *World Energy Issues Monitor* 2016 (www.worldenergy.org/wpcontent/uploads/2016/03/2016-World-Energy-Issues-Monitor-Full-report.pdf)

Zhang Q, Weili T, Yumei W and Yingxu C 2007 External costs from electricity generation of China up to 2030 in energy and abatement scenarios *Energy Policy* **35** 4295–304

Chapter 4

Coal exit health and environmental damage reductions outweigh economic impacts*

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Cheap and abundant coal fueled the industrialization of Europe, North America, and Asia[1]. However, the price tag on coal has never reflected the external cost to society; coal combustion emits more than a third of today's global CO_2 emissions and it is a major contributor to local adverse effects on the environment and public health, such as biodiversity loss and respiratory diseases. Here we show that phasing out coal yields substantial local environmental and health benefits that outweigh the direct policy costs due to shortening of the energy supply. Phasing out coal is thus a no-regret strategy for most world regions, even when only accounting for domestic effects and neglecting the global benefits from slowing climate change. Our results suggest that these domestic effects potentially eliminate much of the free-rider problem caused by the discrepancy between the national burden of decarbonization costs and the internationally shared benefits of climate change impact mitigation. This, combined with the profound effect of closing around half of the global CO_2 emissions gap towards the 2°C target, makes coal phase-out policies attractive candidates for the iterative strengthening of the Nationally Determined Contributions pledged by the countries under the Paris Agreement.

Only a tight cumulative CO_2 emissions budget remains for humanity if warming is to be limited to well below 2°C, or even 1.5°C[2], as stated in the Paris Agreement. However, global greenhouse gas emissions are still rising[3] and the currently pledged Nationally Determined Contributions (NDC) up until 2030 are known to be insufficient to bridge the emission gap to a "Paris compliant" emission pathway[4].

Fossil fuels in general, and coal use in particular, are not only responsible for the bulk of greenhouse gas emissions but are also major contributors to the non-climate environmental footprint of human activity along their whole life cycle, upstream when mining as well as by the combustion itself.

In contrast to climate change damages, these impacts are mainly local and near-term (intra-generational), and may, therefore, figure prominently in policymakers' energy strategy considerations[5]. Considering the full spectrum of positive local health and environmental effects of phasing-out coal could outweigh negative economic effects and therefore help to address the free-riding problem of the *Tragedy of the Global Commons* in the context of international climate policy[6,7]. Moreover, climate policies come with the additional challenge of inter-generational free-riding, since consumption benefits of weak climate policy are enjoyed today, at the expense of reduced welfare of future generations. Here, the near-term characteristics of health and environmental benefits can provide incentives for immediate climate action.

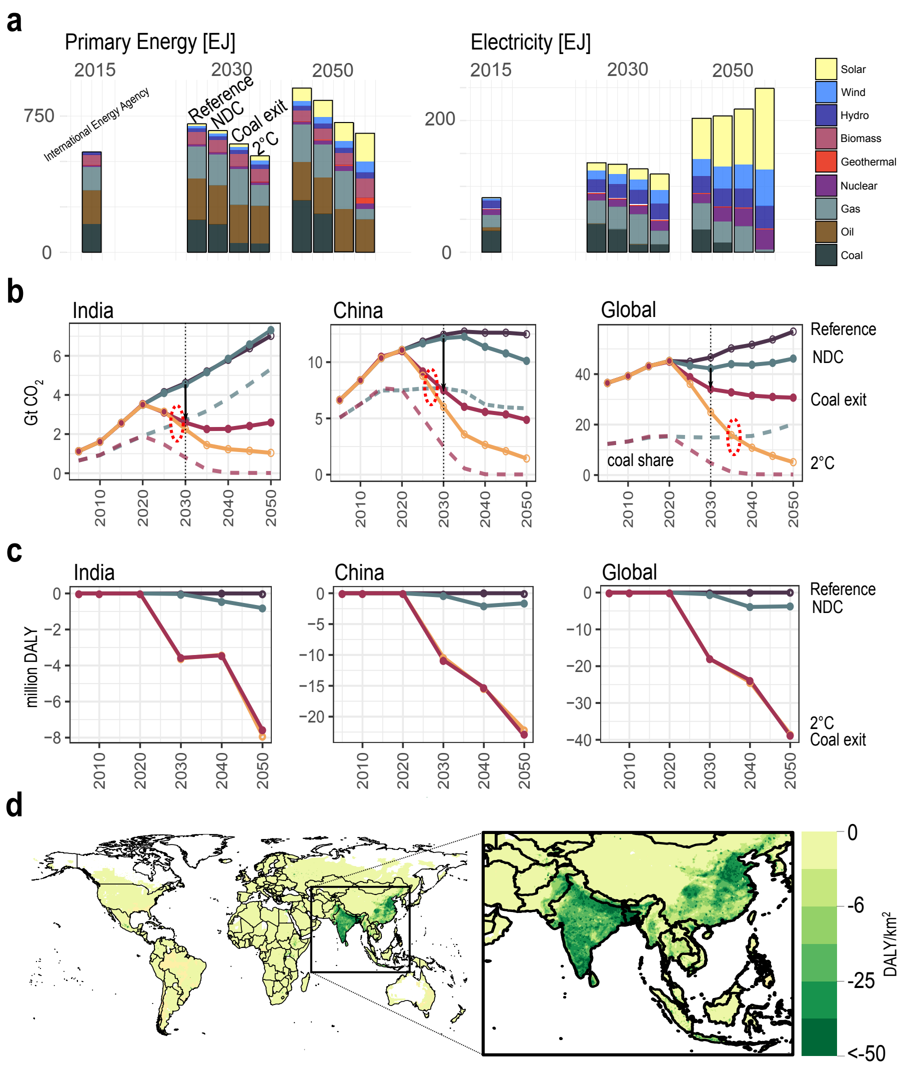
The existing literature has investigated the importance of coal phase-out policies as an early entry point to achieve global mitigation targets in line with the Paris Agreement[8–10]. However, less research has been devoted to the regional effects of phasing out coal on the economy, environment, and human health and the implications for global greenhouse gas emissions.

In this study, we provide an estimate of the relative magnitudes of direct policy cost (macroeconomic consumption losses) compared to indirect social cost savings from the reduced impact on human health and the environment, addressing calls for an integrated approach to energy sustainability[11,12]. Subtracting the direct policy cost from indirect social cost savings, referred to as local co-benefits, results in the net societal effect of the policy intervention. This indicates to what extent the consideration of local co-benefits of climate and energy policies can provide incentives on the country level to pursue ambitious climate policies. Finally, to put these local co-benefits in perspective, we add indicative values of the global Social Cost of Carbon (SCC) of 100 \$/t CO_2, as a metric of the global economic damages of climate change and thus global co-benefits of reducing CO_2 emissions.

We develop an interdisciplinary modeling framework integrating an integrated assessment model (IAM), prospective Life Cycle Assessment Modeling (LCA) and an explicit air pollution model (see the methods section for a detailed description of the framework and SI-1.1 Fig. SI-1 for an illustration of the modeling chain). The consistent modeling framework allows a scenario analysis of both, the direct policy cost and the indirect social cost from the most crucial environmental stressors of alternative climate and energy policy regimes while accounting for interactions and leakage effects between sectors, between regions and over time.

We compare three policy scenarios with a *reference* scenario that does not comprise any additional energy or climate policies. The socioeconomic drivers and assumptions for the energy-economy system (energy demand, economic development) as well as the impact side (population development and demographics, urbanization) are chosen in accordance with the SSP2 'middle-of-the-road' scenario[13]. The *NDC* scenario implements nationally determined contributions as currently pledged until 2030 under the Paris Agreement. After 2030 national mitigation efforts are extrapolated by assuming gradually tightened technology targets and convergence towards an end of the century CO_2 price of 70\$/t. The *2°C* scenario limits the global mean temperature rise by the end of the century to 2°C through cost-effective global uniform carbon pricing across regions and sectors. Finally, we construct the *coal exit* scenario by imposing a 2°C compliant cap on the coal use, while otherwise assuming the implementation of the current policies as in the NDC scenario. This cap models coal phase-out policies that limit coal utilization to a carbon pricing pathway in-line with the 2°C scenario across regions, sectors, and time.

Figure 1: |**Energy system transformation pathways and emissions across scenarios.** **a** Global Primary Energy and Electricity production. **b** Carbon dioxide emissions of India, China and globally. Emissions from coal for the NDC and Coal exit scenarios are displayed by the dashed lines. In the NDC scenario, coal emissions alone exceed the 2°C carbon budget before 2050, as highlighted by the red ellipses. The arrows illustrate the narrowing effect of the coal exit on the emission gap between the NDC and 2°C for the year 2030. The regional CO_2 budgets of the 2°C scenario reflect a cost-optimal allocation calculated endogenously through interactively adjusting a globally uniform carbon price, assuming equal marginal abatement cost curves (see SI-1.1 Fig. SI-6 for the corresponding regional CO_2 price pathways). **c** Air pollution-related health impacts as the difference of million disability adjusted life years (DALY) between policy scenarios and the Reference scenario for India, China, and the world. **d** Spatial distribution of health impact shown in panel **c** for the Coal exit scenario relative to



We find that currently pledged NDCs only have a small transformation effect on primary energy supply and electricity generation, and only lead to marginal reductions in global CO_2 emissions, see Fig. 1**a**, a result well aligned with previous studies[14,15]. (see SI-1.2 Fig. SI-3-5 for the regional results) In particular, emission reductions are small for China (Fig. 1**b** middle column) and negligible for India (left column), whose greenhouse gas intensity reduction target under the NDC is non-binding. Coal utilization stagnates at today's levels and is only slightly reduced compared to the reference scenario. Consequently, coal-related CO_2 emissions alone already exceed the total CO_2 emissions under cost-optimal 2°C compliant policies by 2035 on a global level and even before 2030 for China and India, as indicated by the red circle in Fig. 1**b**.

The coal exit scenario, on the other hand, leads to a substantial transformation of the energy system. Coal is reduced to about one-quarter of today's levels in 2030 and almost completely phased out until 2050. Consequently, primary energy demand is reduced and solar, wind, and especially gas substitute coal in the power sector and oil, gas, and biomass in the industry and buildings sector. As a result, the global CO_2 emission gap between the NDCs and the 2°C scenario is narrowed in the short term, and almost closed for China and India. Even more drastic are the effects on air pollution, as can be seen in the number of mitigated DALY in Fig. 1**c**: Impacts are decreased to similar levels as the 2°scenario, improving global public health by 40 million DALY in 2050, most of which are located in Asia (see Fig. 1**d**). This is the result of the high baseline coal utilization and demographic characteristics (population growth in India; demographic susceptibility in China; overall high population density and urbanization, see SI-1.3 Fig. SI-8-11 for global absolute, regional and sectoral results).

Figure 2: |**Globally aggregated direct policy cost and environmental and health cost/benefits relative to annual GDP purchasing power parity (PPP). a** Direct annual policy cost and globally aggregated monetized values of local health and environmental effects across policy scenarios relative to the Reference scenario. Direct annual policy cost is derived from macroeconomic consumption loss, human health impacts are valued through willingness-to-pay metric and environmental damages are valued through restoration cost. The inner bars show the cost/benefits for the different categories (stressors). For the outer (thick) bars, stressors are grouped by the impact channels, i.e., ecosystem damages, human health, and direct policy cost. Solid black lines indicate the resulting net societal effect: the aggregated local co-benefits minus direct policy cost. For the red lines, we add the global benefits in the form of the SCC of 100US$/t to the net societal benefits. The whiskers indicate the uncertainty ranges of the net societal benefit from the translation of human health and environmental impacts into the social cost. **b** Benefits of the coal-exit scenario for the year 2050 in absolute terms.

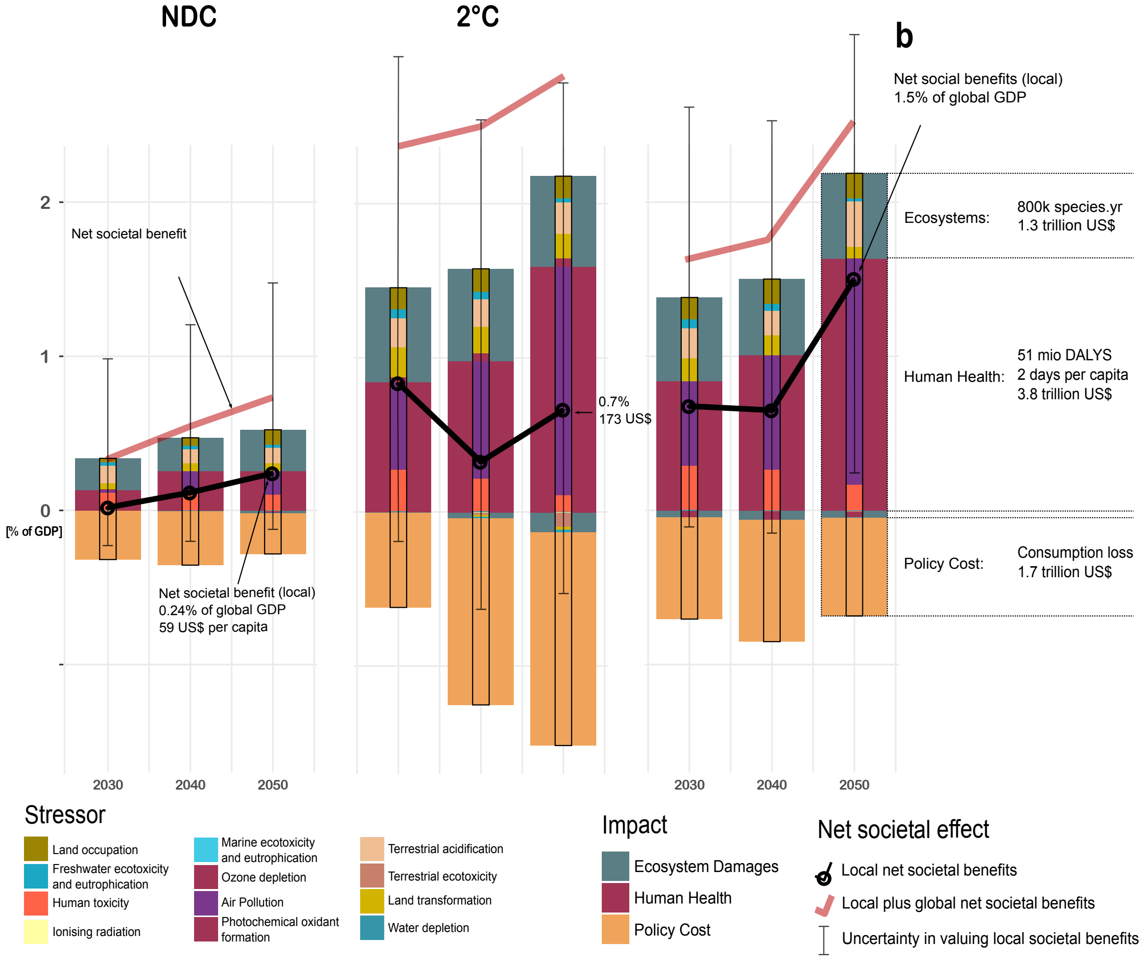


Figure 3: |**Regional analysis of local co-benefits and direct policy cost relative to annual GDP PPP.** Discounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios until 2050 with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits.

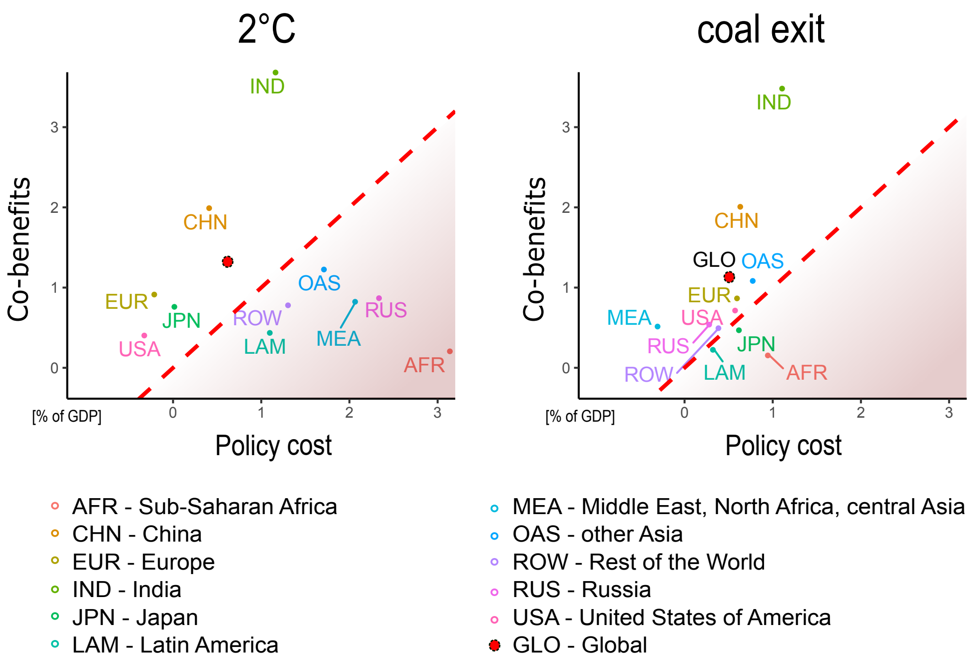


Fig. 2 shows that the NDCs only yield small air pollution-related societal cost co-benefits. Nevertheless, other local human health and environmental co-benefits in combination with low direct policy cost lead to a net positive societal effect (black line, see SI-1.4 Fig. SI-12-25 for stressor category and sectoral results and Fig. SI-26-28 for regional results).

In the 2°C scenario, on the other hand, direct policy cost increase to 1.5% of GDP PPP in 2050. However, the associated higher local co-benefits of mainly air pollution, as well as human toxicity, terrestrial acidification, and land-related biodiversity benefits result in positive global aggregate net societal benefits, reaching 0.5% of GDP PPP in 2050.

In the short term, the coal exit scenario has a similar effect in terms of local benefits and direct policy cost as a cost-effective 2°C scenario. However, in contrast to the 2°C scenario, no further long-term transformation e.g. phase-out of gas or transport decarbonization, is induced, highlighting the role of coal phase-out policies as an early entry point, which needs to be complemented by stringent climate policies to avoid carbon lock-in of other fossil fuels[16,17].

This results in global net societal benefits of 3.4 trillion US$ (1.5% of GDP PPP) in 2050, equal to 370 US$ per capita on average. The main reason for these high benefits is lower mitigation cost through low corresponding prices of CO_2 in the long term compared to the 2 °C goal (see SI-1.1 Fig. SI-6). To illustrate the effect of climate change damages, we add a global uniform SCC of 100 US$/t CO_2 (see 1.4.4 for a discussion on SCC). The red line illustrates adding these reductions to the local benefits. Under this assumption, the gross local benefits are in the same order of magnitude as the SCC for all scenarios (see SI-1.4 Fig. SI-29). Additionally, the 2°C scenario outperforms the coal exit scenario, reaching a net benefit of 2.8% of GDP PPP in 2050. However, this would flip in 2050 if SCC of around 50 US$/t CO_2 or lower are assumed due to lower long term mitigation cost mentioned above. The ranges reflect the uncertainty introduced by the monetary valuation of impacts (see SI-1.5 for a detailed discussion of the uncertainty of the modeling framework). Although the uncertainty is substantial, the positive net social benefit of exiting coal is robust. Only very optimistic assumptions about the cost of environmental damages and human health push them close to zero in 2050 and below in the previous years, while pessimistic assumptions raise these costs by a factor of two to three.

Fig. 3 shows that almost all world regions exceed their direct policy cost of exiting coal (mostly GDP loss and higher energy system investment cost) by human health and environmental benefits until 2050 (break-even is represented by the dashed line, see SI-1.4 Fig. SI-30 for the uncertainty analysis and SI-1.1 Fig. SI-7 for the decomposition of regional and global policy costs).

Only Sub-Saharan Africa, Latin America and Japan, regions with low air quality-related health benefits, face higher costs than benefits (see SI-1.4 Fig. SI-32 for all time steps and scenarios). The 2°C scenario, on the other hand, shows a more scattered picture; China and India (high air quality benefits), as well as Europe, Japan, and the USA (low direct policy cost) yield net positive societal effects while the rest of the regions face higher direct policy cost than local co-benefits. That being said, when the global benefits of reduced climate change damages are taken into account based on a global uniform SCC, all regions break even (see SI-1.4 Fig. SI-31).

To conclude, we find an accelerated global coal phase-out to be a policy with immediate and strong CO_2 emission reduction effects, significantly narrowing the gap between the NDCs and a 2°C compliant pathway. Impressively, the cost of such a policy is overcompensated through environmental and public health co-benefits, resulting in a global net positive societal effect even if climate benefits were to be ignored.

These results have significant bearing on international climate policy. For most countries, and in particular, the world's largest CO_2 emitters (China, India, Europe, USA), we find local co-benefits of all examined climate policy scenarios (2 °C, coal exit) of such large magnitude that they can play an important role to overcome the inter-regional and inter-generational free-rider problem of climate policy: Their domestic monetized environmental and health benefits exceed direct policy cost, thus creating an incentive to act even if others do not. Exiting coal emerges here as a particularly valuable climate policy entry point, as it reduces CO_2 emissions at relatively low cost while reaping most of the local environmental co-benefits. Additionally, in contrast to climate impacts, these local co-benefits are not particularly sensitive to different discount rates, stimulating immediate action (see SI-1.2 Figure SI-32).

In addition, the tangibility and possible unifying nature of coal phase-out policies could make them particularly interesting for the next round of the Nationally Determined Contributions. Here, front-runner countries could agree on ambitious individual time-lines and/or a majority is formed, committed to phasing out coal at a similar pace to avoid market distortions (see the Powering Past Coal Alliance[10]). At the same time, the local nature of the co-benefits and the identification as a robust "no-regret" strategy can support the call of national, regional and local groups for the introduction or strengthening of coal phase-out policies - an important part of the puzzle to overcome known issues of political economy of coal, such as dysfunctional governments[10], vested interests of (often state-owned) power companies, distributional (equity) effects and the difficulties to enforce the polluter pays principle caused by complex emission-impact relationships. This complexity causes various uncertainties in the proposed framework, particularly regarding the valuation of environmental damages, and future research should be devoted to further increase the robustness of results.

While the coal exit is a crucial early entry point, it is imperative that it be complemented by further climate policies to reach a goal in line with the Paris Agreement and to avoid the lock-in of other fossil fuels. Additionally, the societal benefits of mitigation action further increase if avoided climate damages are taken into account. Therefore, a holistic response to the climate and environmental crisis will eventually have to achieve almost full-scale decarbonization of power supply and thus also entail a deep reduction of not only coal, but also oil and gas, and address non-electric energy demands in transportation, buildings, and industry sectors, as well as resource efficiency.

Our results second the call for an integrated assessment of climate protection and multiple, complementing benefits of sustainable development and echo the call for policymakers to inject this concept into climate negotiations and policy design.

1. Methods

The modeling framework is designed as an interdisciplinary model chain, building on research of many disciplines. This study contributes to the development of the individual modeling steps, as described in the subsections below, and combines them in a consistent framework, thus facilitating a comprehensive assessment of economic, environmental and human health effects of policies (see SI-1.1 Fig. SI-1 for a schematic of the modeling framework).

The effects of policies on the climate, energy system and economy are derived with the REMIND IAM system. REMIND is a hybrid modelling system that represents macro-economic drivers of growth, investment and energy demand in 11 world regions in combination with a technology-rich bottom-up representation of energy systems[18]. The land-use related effects are captured by running REMIND in conjunction with an emulator of the global land and water-use model MAgPIE, ensuring consistency between the energy-economy-climate and land, water-use systems. All results, including technology specific cost assumptions, can be found in the SI results files. The levelized cost of electricity for selected technologies are available in the SI-1.2 Table SI-2.

The effects on non-climate environmental and human health impacts are analyzed by a dual approach, focusing on a holistic representation of life-cycle impacts: (1) Air pollutant emissions, the most significant contributor to local health impacts, are represented by source in REMIND[19]. Resulting human health impacts are estimated via an atmospheric chemistry model and non-linear, disease specific epidemiological response functions[20]. (2) Other human health and ecosystems damage impact channels are based on LCA of all regional energy systems[21] using the ReCiPe methodology[Goedkoop2013]. Including the whole life cycle is crucial since the trend towards renewable energy generation technologies shifts impacts from direct emissions (e.g., burning fossils) to indirect emissions (e.g., construction of energy infrastructure, or land-use for bioenergy).

We evaluate all impacts in terms of their effect on human health, measured by Disability Adjusted Life Years (DALY), and environmental damage, in potential species loss over time. We then monetize health effects by willingness-to-pay valuation, environmental damages though potential land restoration cost, and direct policy cost through macroeconomic consumption loss, constructing a unified metric of social cost. Feedback from damage to the environment and human health (e.g. workforce loss, health expenditures) on GDP is not considered.

1.1. Energy-Economy-Climate Modeling

The starting point of the model chain is the global energy-economy general equilibrium model REMIND[22] linking a macro-economic growth model with a bottom-up energy system model[18,23]. It is an integrated assessment model, built around a Ramsey-type growth macroeconomic core which maximizes inter-temporal welfare. The associated energy demands are fulfilled by the energy system model covering primary, secondary and final energy markets as well as renewable energy potentials. Here, more than 50 conversion technologies are considered including the development of system characteristics and cost. Major drivers of inertia and path dependencies are modeled by representing full capacity vintage structure, technological learning, and technology ramping cost, see the SI for result files.

1.2. Life Cycle Assessment

Life Cycle Assessment is an established method to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. To this end, inventories of environmentally relevant flows (i.e., emissions, natural resources and waste) to and from the biosphere are compiled for specific (industrial) products[24]. In a second step, the flows are characterized by their effect on human health and ecosystem quality according to impact assessment methods.

To calculate the life-cycle impacts of activities represented in REMIND, we start with the ecoinvent database (version 3.5, cut-off system model)[21], supplemented with additional datasets for expected future technological development, such as in carbon capture and storage[25]. This database allows us to calculate both the direct emissions of energy generation and use, and indirect emissions due to plant construction and maintenance, fuel extraction, refinement, and transport, as well as all other material and energetic inputs needed for the policy scenarios. Using an open source tool-chain, described in the SI, we used the policy scenario outputs to systematically modify the industrial supply chains given in ecoinvent to account for future energy system changes. Specifically, we used REMIND policy scenario outputs at each time step a) to change the technology shares in electricity grid mixes; b) to change the effectiveness of pollution control devices in electricity generation technologies, and c) to change the fuel or conversion efficiencies of electricity generation technologies. In cases where REMIND did not provide direct estimates of emissions, we used changes in fuel efficiency as proxies to linearly adjust emission levels. As LCA databases form an interconnected global supply chain, our changed electricity generation is used throughout the database, making all consuming technologies cleaner. However, we note that we did not alter non-electricity technologies to account for future changes in efficiency or pollution control, and as such the LCA results are conservative, in that most industrial processes are expected to be cleaner than we estimate in the future. We use our modified database to calculate the impact of one kilowatt-hour of high-voltage electricity at each time step for each policy scenario, using human health and ecosystem quality endpoint values from the ReCiPe life cycle impact assessment method[26]. All results, including technology and region specific mind-, end-point, and monetized results can be found in the SI files.

1.3. Air pollution

We model the air pollution emissions and the development of air pollution control policies as well as technology research, development, deployment and diffusion through the change of technology-specific aggregated emission factors over time derived from the GAINS model[27]. See Rauner et al.[19] for an extended description of the air pollution model chain.

The resulting air chemistry, influenced by these air pollution emissions, is modeled employing the global linearized atmospheric chemistry transport model TM5-FASST[28] covering SO_2, NO_x, black carbon(BC), organic matter(OM), NH3, volatile organic carbon (VOC), CH4 and primary $PM_{2.5}$.

The air pollution related health impact assessment is based on the Global Exposure Mortality Model developed by Burnett et al.[20]. Disease end-points considered are ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD) and lung cancer (LC), and for children under 5, acute respiratory lung infection (ALRI). The toxicity of $PM_{2.5}$ is assumed to be uniform with regards to inhaled mass (exposure). The O_3

health impact assessment is based on the seasonal (April–September) average daily 1-hr maximum concentrations[29]. We calculate 192 million DALY for the year 2015 which is in line with the research from Burnett et al.[20] (see SI-1.1 Fig. SI-2).

The relative risk R is a function of the concentration c calculated through the Global Exposure Mortality Model which shapes are determined by θ_d, α_d,μ_d and ν_d, the disease endpoints d specific results are shown in Fig. 5:

$$R(c)d = \begin{cases} 1 & \text{if } c <= c_{cf} \\ e^{\theta_d * log(c/\alpha_d+1)/(1+e^{-(c-\mu_d)/\nu_d)})} & \text{if } c > c_{cf} \end{cases}$$

The Global Exposure Mortality Model has a supra-linear shape and drop to one at a theoretical minimal risk concentration c_{cf} of $2.4\mu g/m3$. Multiplying the attributable fraction a with the baseline mortality rate[30] y_0 and exposed population p[31] to calculate mortalities:

$$a_d = \frac{R_d - 1}{R_d}$$

$$\Delta m = \sum_{i=1}^{z} y_{0,d}\, a_d\, p$$

We assess not only mortality but also morbidity in a consistent integrated framework through the disability adjusted life year (DALY) concept. This is an aggregate measure combining the years lost through premature death compared to the life expectancy and the years living less than optimal health. We calculate the disease z and demography d specific DALY for every time step and region by relating them to the base year premature deaths DALY ratio reported in the Global Burden of disease study of 2017[32].

$$DALY_{r,t} = \sum_{i=1}^{z}\sum_{i=1}^{d} DALY_{z,d,r,2015}/m_{z,d,r,2015} * m_{z,d,r,t}$$

1.4. Monetary valuation of impacts

1.4.1. Human Health

We employ a willingness-to-pay approach to translate human health impacts into social cost. Our calculations are based on a meta-analysis of stated-preference studies by the Organisation for Economic Co-operation and Development which estimate the value of a statistical life (VSL)[33]. In contrast to revealed preference methods, these number are not based on empirical data, however, they can be applied to a large set of the population and regions. The recommended base value derived by the meta regression of available literature is 3.6 million US$ for the EU in 2005 with a low and high estimate range from 1.8 to 5.4 million US$, which we use for the uncertainty. We relate the VSL to the baseline DALY/mortality ratio and thus calculate the value of one DALY, about 120 k US$ for the EU-28 in 2005. VODALY reflect the amount a person is willing to pay to mitigate the mortality risk of one life year and the risk of one life year of non-optimal health. These values are adjusted over country and time using the spatial unit value transfer method described in the section below.

1.4.2. Environment

The environmental impact is measured in potential biodiversity loss [species.year] which can be interpreted as the number of species that has a high probability of disappearing due to unfavourable conditions. The concept is applied to the global terrestrial species density of 1.6 million species on 108.4 million km2 area. A main simplification is the assumption of an uniform distribution of terrestrial species on the global land surface. More research should be devoted to increasing the spatial detail through region specific analysis of ecosystem damage, effects on aquatic animals and methods to couple them to Energy-Economy-Climate models.

We value the potential biodiversity loss by the associated marginal habitat restoration cost. Essentially, the value we use reflects how much it costs to restore the habitat where a certain biodiversity is likely to reemerge once it was diminished by human influence. Ott et al.[34] calculated cost for different land-use types for the EU, building on the work of Köllner[35]. These values are adjusted using the spatial unit value transfer method described in the next section. We extract the marginal cost to improve the habitat for one species.year per m2 from "built up land" for an average land-use mix for a ten year period. The associated cost of 0.165 US$2005/(PDF m2 year) can now be divided by the global species density which results in 11.15 million US$2005/species.year. We use the lowest and highest restoration cost land-use types from 'built up land' as uncertainty ranges, these are 0.018 for "integrated arable" and 0.9 US$2005/(PDF m2 year) for 'forest edge'.

1.4.3. Spatial unit value transfer

The lack of consistent studies estimating both the human health and environmental monetization V for all regions of the world, necessitates a method to spatially and temporally transfer the employed valuation. We use the unit value transfer method, adjusting with country specific GDP purchasing power partity per capita Y and an elasticity ε of 1.2 and 0.8 for countries with a lower and higher income than the reference region EU-28 in the base year 2005. The resulting valuation coefficients aggregated over world regions can be found in the SI-1.1 Table SI-1.

$$V_{c,t} = V_{EU,2005} \frac{Y_{c,t}}{Y_{EU,2005}}^{\varepsilon}$$

1.4.4. Global impacts

We add a global uniform SCC to illustrate the effect of the scenarios on global climate change damages. The estimates vary widely in literature without conclusive estimates. Although meta studies estimate the SCC in the range of around 40 US$/t[36], recent research points towards higher estimates and argues for a lower bound of 125 US$/t[37]. In this study, the global climate change damages are used as a hallmark to which local co-benefits are compared to. We therefore opt for a global uniform value of 100 US$/t and keep it constant over time.

1.5. Uncertainty

The modeling framework is subject to various uncertainties embodied in every step of the modeling chain, from economy-energy-climate modeling to impact quantification and monetary valuation.

The most relevant uncertainties of the economy-energy-climate model for this study are technology cost, renewable energy potentials, technological learning and scale-up rates[38], since they affect what technologies substitute coal, the inertia of the energy system, and associated mitigation cost. However, multi-model studies showed that the general decarbonization strategies are robust across many different models[39].

On the impact side of the modeling framework, the air pollution related human health impacts have received a lot of attention in the research community due to its identification as one of the major causes of global premature mortality. We are therefore able to model the cause effect chain of emissions, concentrations and human health impacts spatially explicit and validate the results with latest research in this field.

The life cycle assessment modeling of other human health and environmental damages is based on an extensive data set supplied by sector experts and constantly reviewed and validated. Uncertainty of the emissions part mainly lies in difficult attribution of emissions, lack of spatial data and the consistent coupling with the IAM system. Translating the emissions into impacts is based on established methods, however, they rely on static simplified models and especially aggregating these impacts into the two categories human health and environmental damages is subject to higher uncertainty. Future research should be devoted to the consistent prospective coupling of LCA and IAM models as well as the development of time, region and socio-economic development specific characterization factors.

The highest uncertainty of this framework is introduced by the monetary valuation of impacts. The valuation of human health is based on a synthesis of results of stated-preference approaches and not empirical data. The lack of consistent data set further requires a value transfer over space and time, which lacks other factors than GDP. The environmental damage valuation is subject to the same transfer uncertainty as well as uncertainty in the restoration cost data. Further research should be devoted to model environmental quality and its monetary value. Another source of uncertainty is how much human health and environmental damages would affect the economy. We only value these impacts but do not implement a feedback.

2. Data availability statement

The data supporting the findings of this study are available within the paper, its supplementary information files and in the following repositories. Energy-economy-climate modeling: REMIND (github.com/remindmodel/remind); Life Cycle Assessment: Notebooks and data for LCA calculations (github.com/rauner/holistic-coal-exit); Air pollution: Air pollution emissions, concentrations, human health impact (github.com/rauner/air-pollution).

3. Code availability

The code supporting of this study is available within the paper, its supplementary information files and in the following repositories. Energy-economy-climate modeling: REMIND (github.com/remindmodel/remind); Life Cycle Assessment: Notebooks and data for LCA calculations (github.com/rauner/holistic-coal-exit), Brightway2 (bitbucket.org/cmutel/brightway2), Wurst (github.com/IndEcol/wurst), rmnd-lca (github.com/Loisel/rmnd-lca); Air pollution: Air pollution emissions, concentrations, human health impact (github.com/rauner/air-pollution); Spatial unit value transfer: Value transfer (github.com/rauner/air-pollution/blob/master/calcMonetization.R).

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6. Author Contributions

S.R., N.B., and G.L. designed the research. S.R. designed the modeling framework and performed the integrated assessment analysis. S.R. and R.V.D. performed the air pollution analysis. S.R., A.D., and C.M. performed the life cycles assessment analysis. S.R. created the figures and wrote the paper with inputs and feedback from all authors.

1. Pomeranz, K. *The Great Divergence.* (Princeton University Press, 2009).

2. Masson-Delmotte, V., Zhai, P. & Pörtner, H. O. IPCC, 2018: Global warming of 1.5°C. An IPCC 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 cli. (2018).

3. Le Quéré, C. *et al.* Drivers of declining CO2 emissions in 18 developed economies. *Nature Climate Change* **9**, 213–217 (2019).

4. United Nations Environment Programme. *UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi.* (2018).

5. Griggs, D. *et al.* Sustainable development goals for people and planet. *Nature* **495**, 305–307 (2013).

6. Lloyd, W. Two lectures on the checks to population : delivered before the University of Oxford. (1833).

7. Brousseau, E., Dedeurwaerdere, T., Jouvet, P.-A. & Willinger, M. Introduction: Global Environmental Commons: Analytical and Political Challenges in Building Governance Mechanisms1. in *Global environmental commons* 1–28 (Oxford University Press, 2012).

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

9. Edenhofer, O. *et al.* Closing the emission price gap. *Global Environmental Change* **31**, 132–143 (2015).

10. Jewell, J., Vinichenko, V., Nacke, L. & Cherp, A. Prospects for powering past coal. *Nature Climate Change* **9**, 592–597 (2019).

11. McCollum, D. L., Krey, V. & Riahi, K. An integrated approach to energy sustainability. *Nature Climate Change* **1**, 428–429 (2011).

12. Editorial. Sustainable development through climate action. *Nature Climate Change* **9**, 491–491 (2019).

13. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168 (2017).

14. Rogelj, J. *et al.* Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications* **8**, 15748 (2017).

15. Vrontisi, Z. *et al.* Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. *Environmental Research Letters* **13**, 044039 (2018).

16. Tong, D. *et al.* Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature* **572**, 373–377 (2019).

17. Luderer, G. *et al.* Residual fossil CO 2 emissions in 1.5-2 °c pathways. *Nature Climate Change* **8**, 626–633 (2018).

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

19. Rauner, S., Hilaire, J., Klein, D., Strefler, J. & Luderer, G. Air Quality Co-benefits of Ratcheting-up the NDCs. *Climatic Change (in review).*

20. Burnett, R. *et al.* Global estimates of mortality associated with long-

term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences* **115**, 9592–9597 (2018).

21. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* **21**, 1218–1230 (2016).

22. IAMC. Model Documentation - REMIND.

23. Bauer, N., Baumstark, L. & Leimbach, M. The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds. *Climatic Change* **114**, 145–168 (2012).

24. Heijungs, R. & Suh, S. *The Computational Structure of Life Cycle Assessment.* vol. 11 280 (Springer Netherlands, 2002).

25. Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A. & Vuuren, D. P. van. Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environmental Science & Technology* **52**, 4989–4995 (2018).

26. Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J. & Zelm, R. van. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 133 (2009).

27. Amann, M. Greenhouse gas and air pollution interaction and synergies (GAINS). 0–43 (2012). url: http://www.ec4macs.eu/content/report/EC4MACS_Publications/MR_Finalinpdf/GAINS_Methodologies_Final.pdf

28. Van Dingenen, R. *et al.* TM5-FASST: A global atmospheric source-receptor model for rapid impact analysis of emission changes on air quality and short-lived climate pollutants. *Atmospheric Chemistry and Physics* **18**, 16173–16211 (2018).

29. Jerrett, M. *et al.* Long-Term Ozone Exposure and Mortality. *New England Journal of Medicine* **360**, 1085–1095 (2009).

30. World Health Organization. WHO Mortality Database. (2012).

31. KC, S. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* **42**, 181–192 (2017).

32. WHO. Global Health Estimates 2016: Deaths by Cause, Age, Sex, by Country and by Region, 2000-2016. Geneva, World Health Organization; 2018. (2018).

33. OECD. *Mortality risk valuation in environment, health and transport policies.* vol. 9789264130 1–139 (OECD Publishing, 2012).

34. Ott, W., Baur, M. & Yvonne, K. New Energy Externalities Developments for Sustainability - Deliverable D.4.2. 'Assessment of Biodiversity Losses'. (2006). url: http://www.needs-project.org/RS1b/RS1b_D4.2.pdf

35. Koellner, T. Land use in product life cycles and its consequences for ecosystem quality. *The International Journal of Life Cycle Assessment* **7**, 130 (2002).

36. Tol, R. S. J. The Economic Effects of Climate Change. *Journal of Economic Perspectives* **23**, 29–51 (2009).

37. Bergh, J. C. J. M. van den & Botzen, W. J. W. A lower bound to the

social cost of CO2 emissions. *Nature Climate Change* **4**, 253–258 (2014).

38. Krey, V. *et al.* Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* **172**, 1254–1267 (2019).

39. IPCC. *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 University Press, 2014).

Coal exit health and environmental damage reductions outweigh economic impacts

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Keywords: coal exit, coal phase-out, sustainable development, co-benefits, life cycle assessment

SI-1 Supporting Information

SI-1.1. Methods

Figure SI-1: |**Modelling framework.** Modelling framework of the cause effect chain of energy-economy-climate to monetized health and environmental impacts. The Integrated Assessment Energy-Economy Climate model REMIND is the starting point of the modelling chain. The policy cost are directly calculated from REMIND through climate policy induced consumption losses relative to the no policy Reference scenario. The right path represents the specific air pollution human health model chain, including the simplified Chemical Transport model and spatial population, urbanization and demography data. The middle path illustrates the Life Cycle Assessment model which covers non-air pollution human health impacts and ecosystem damages.

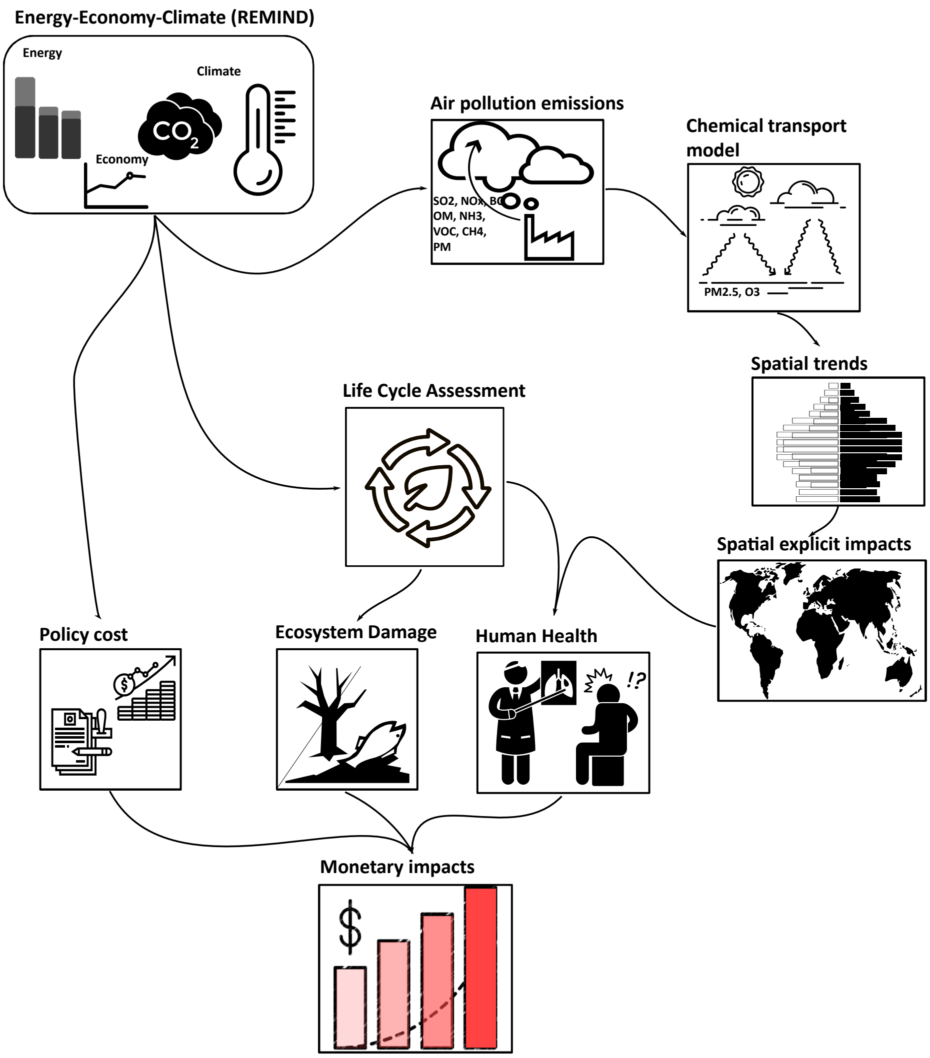
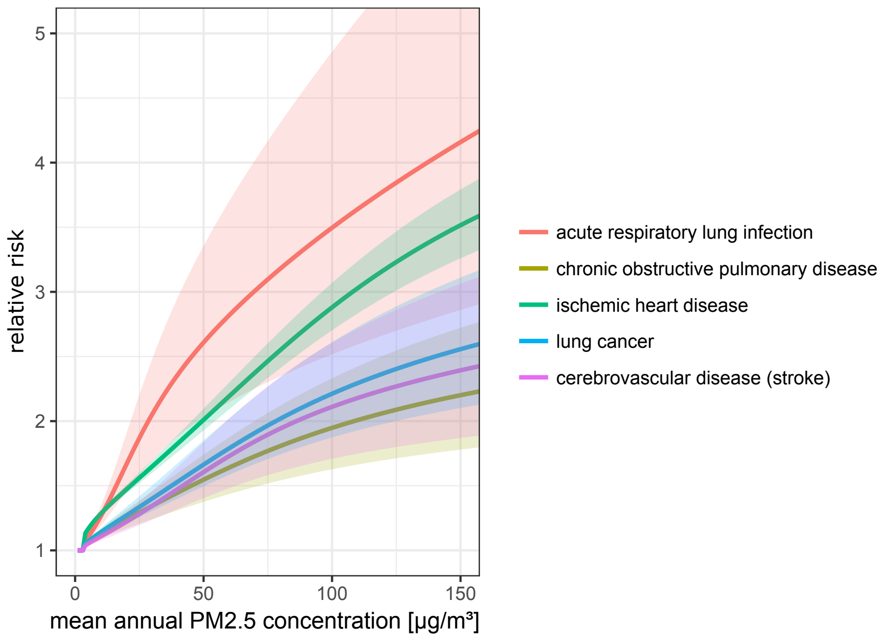


Table SI-1: |**Value transfer coefficients.** Value transfer coefficients of the Reference case for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) in 2015, 2020, 2030, 2040 and 2050. They are applied to the base value of human health 118421.1 US$ per VDALY and the ecosystem damages of 111,486,487.2 US$ per species.yr.

region	2015	2020	2030	2040	2050
LAM	0.500152	0.386202	0.513897	0.666233	0.858463
OAS	0.289746	0.343485	0.452139	0.580002	0.73834
AFR	0.104607	0.108863	0.155965	0.221625	0.320949
EUR	0.954087	1.025294	1.212767	1.429472	1.654259
ROW	1.084928	0.814886	0.962879	1.137768	1.333285
MEA	0.519368	0.575502	0.746901	0.925411	1.109441
CHN	1.275278	1.422803	1.669215	1.891424	2.090629
IND	0.106028	0.132382	0.230956	0.360532	0.527048
JPN	1.169837	1.216918	1.354231	1.474302	1.606203
USA	1.545993	1.652051	1.840732	1.976144	2.083858
RUS	0.55785	0.688134	1.015309	1.352588	1.6276

Figure SI-2: |**Global Exposure Mortality Model@Burnett2018.** Integrated exposure response functions describing the relationship between annual mean ambient $PM_{2.5}$ and relative risk of the five disease endpoints considered. Shading indicate the uncertainty ranges around the employed medium estimate.



SI-1.2. Energy-Economy-Climate Modeling

Table SI-2: |**Levelized cost of electricity (LCOE).** Global average generation LCOE in $/MWh for selected technologies of a new power plant build in the time step. LCOEs do not include a CO_2 price and other taxes but storage cost associated with renewable energy penetration.

Scenario	Power generation technology	2015	2030	2050
Reference	Coal|Pulverized Coal|w/o CCS	63.81	69.15	77.85
NDC	Coal|Pulverized Coal|w/o CCS	63.81	68.72	74.88
Coal exit	Coal|Pulverized Coal|w/o CCS	61.85	60.91	60.49
2°C	Coal|Pulverized Coal|w/o CCS	63.81	66.24	88.08
Reference	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	61.80	70.72
NDC	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	63.18	72.12
Coal exit	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	66.20	74.52
2°C	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	64.88	73.63
Reference	Solar|PV	76.89	43.36	35.83
NDC	Solar|PV	76.89	41.74	35.69
Coal exit	Solar|PV	77.02	41.47	35.87
2°C	Solar|PV	76.89	41.77	36.36
Reference	Wind	64.58	56.93	54.82
NDC	Wind	64.58	56.25	54.66
Coal exit	Wind	64.58	56.05	54.58
2°C	Wind	64.58	54.52	54.13

Figure SI-3: |**Primary energy.** Primary energy mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

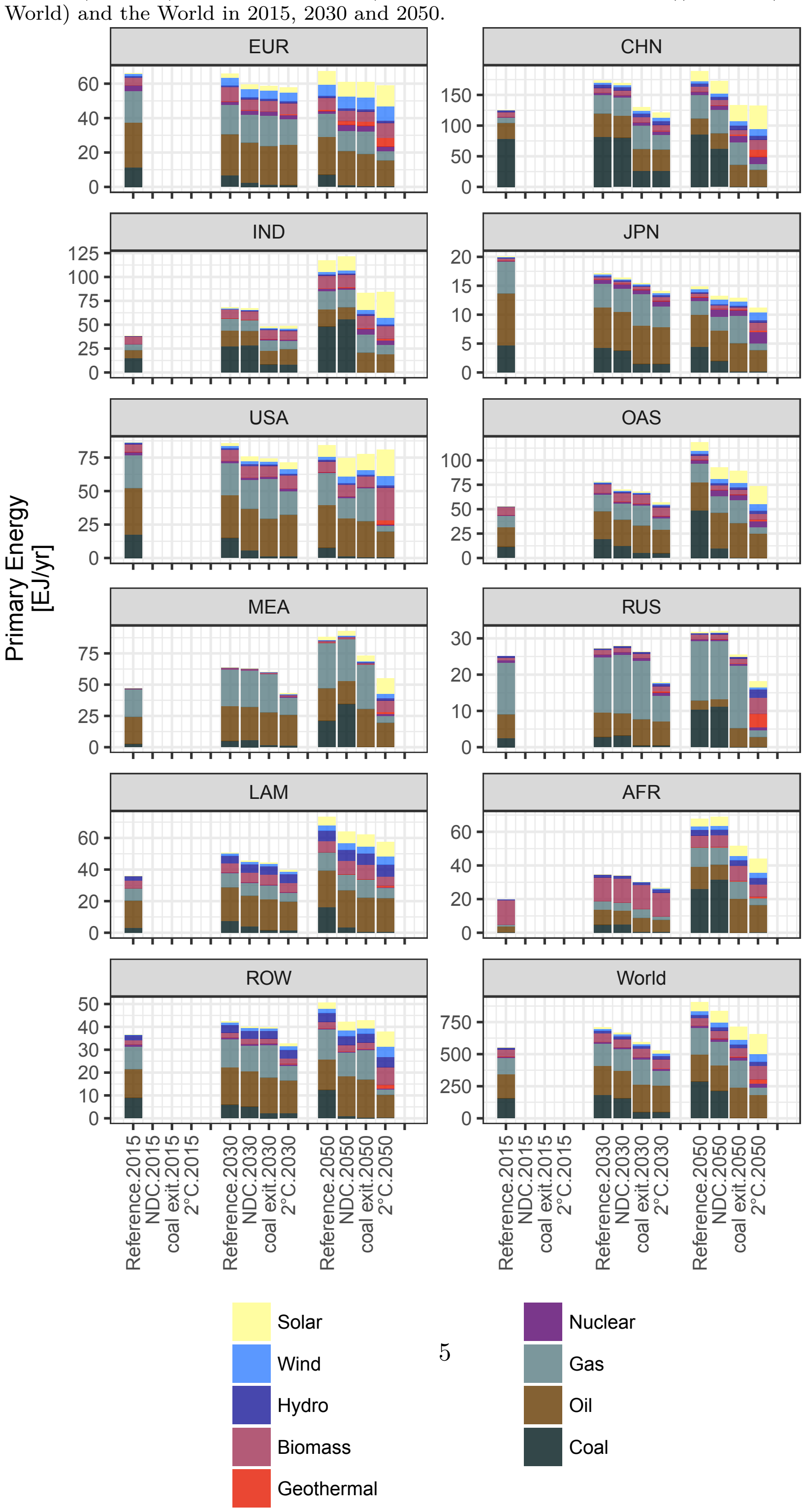


Figure SI-4: |**Secondary energy - electricity.** Secondary energy - electricity mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

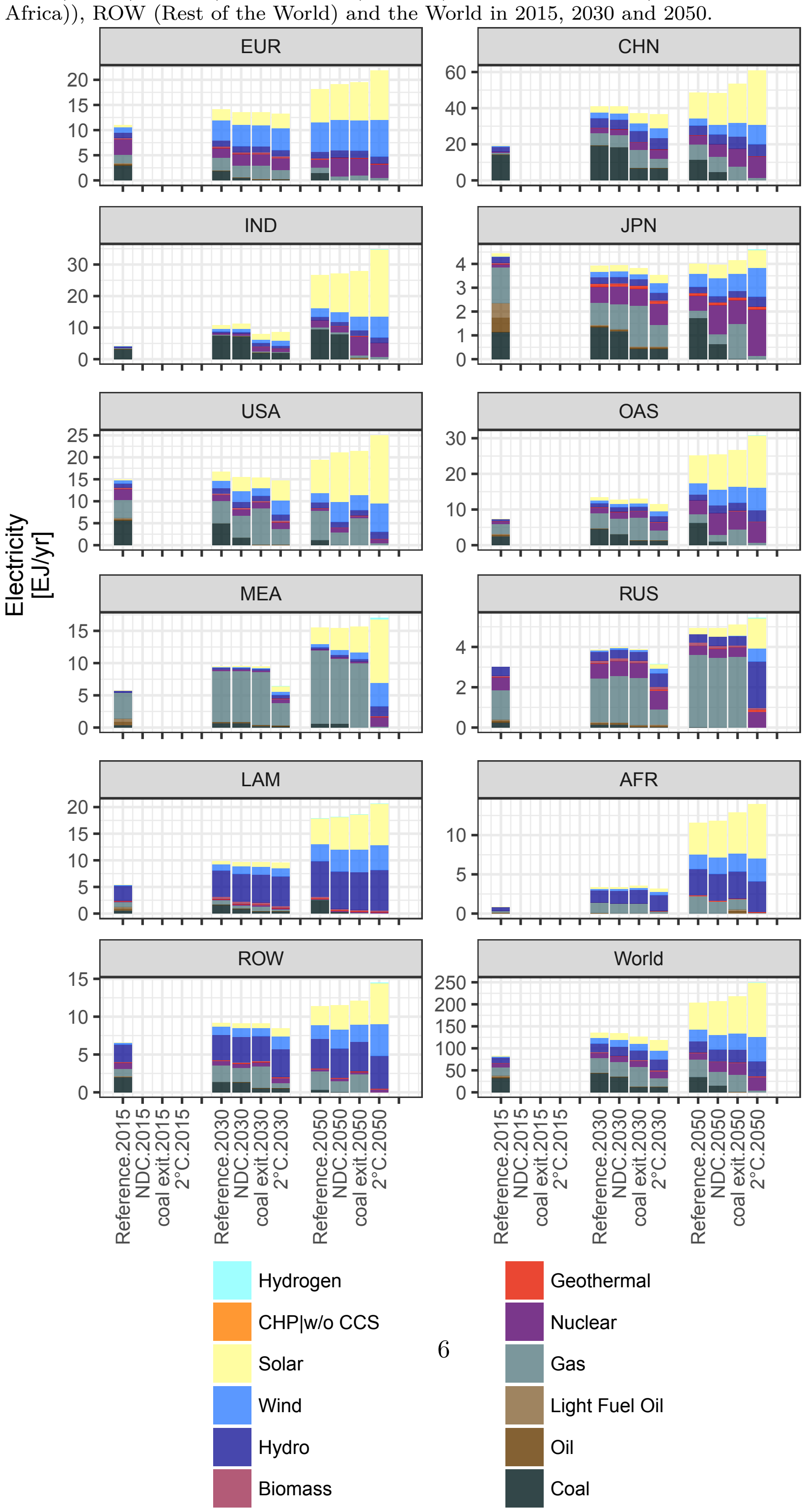


Figure SI-5: |**Carbon dioxide (CO_2) emissions.** CO_2 emissions for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050. The share of coal related emissions is indicated by the dashed line.

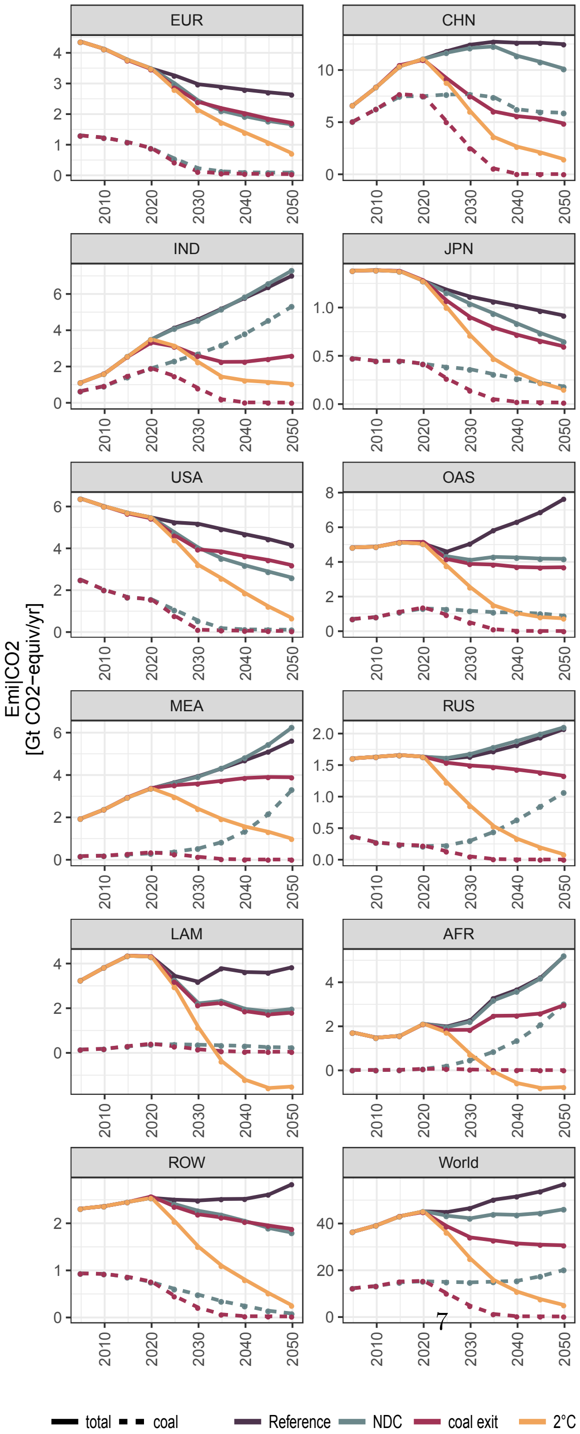


Figure SI-6: |**Carbon dioxide (CO_2) prices.** CO_2 prices for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050.

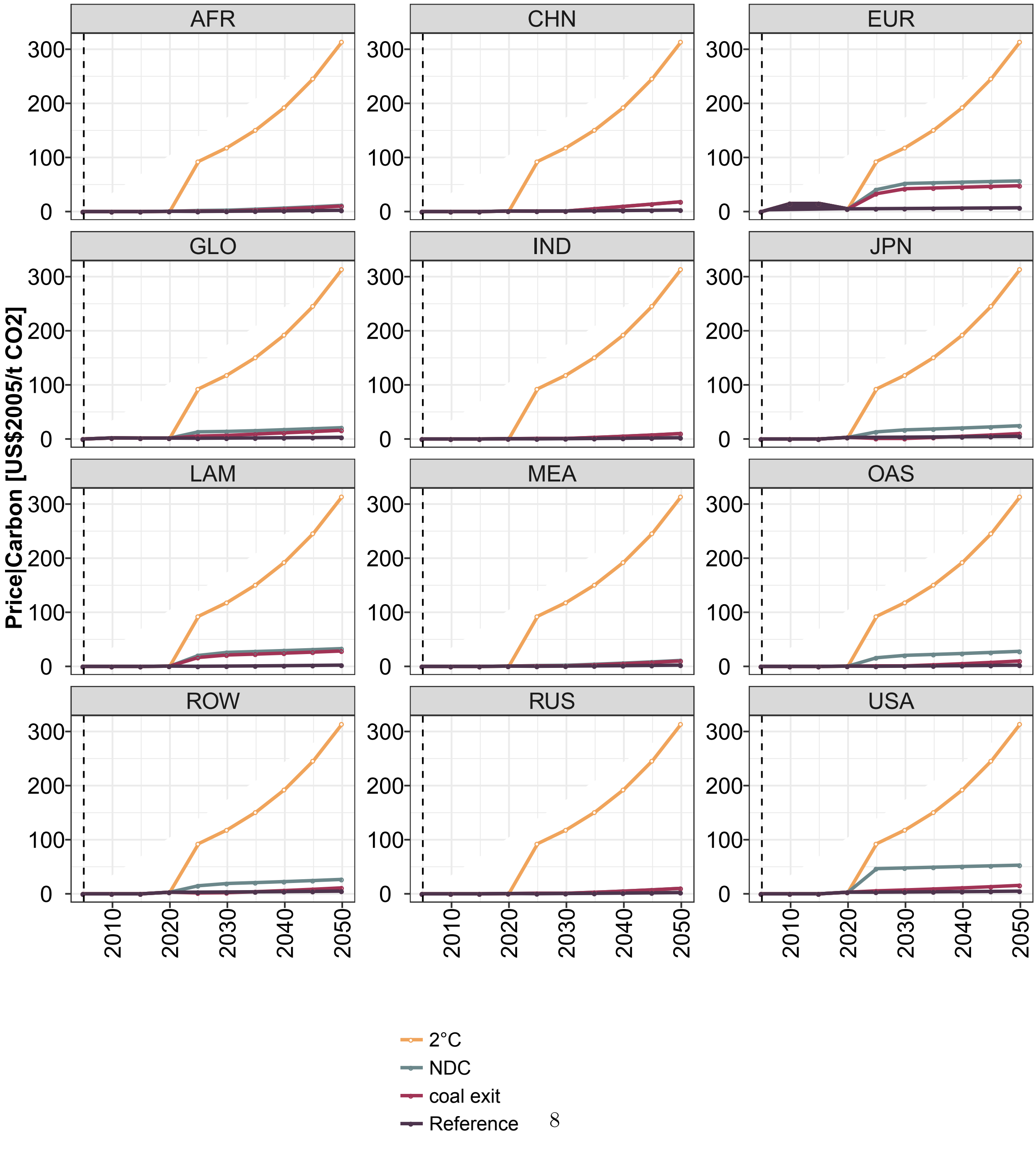
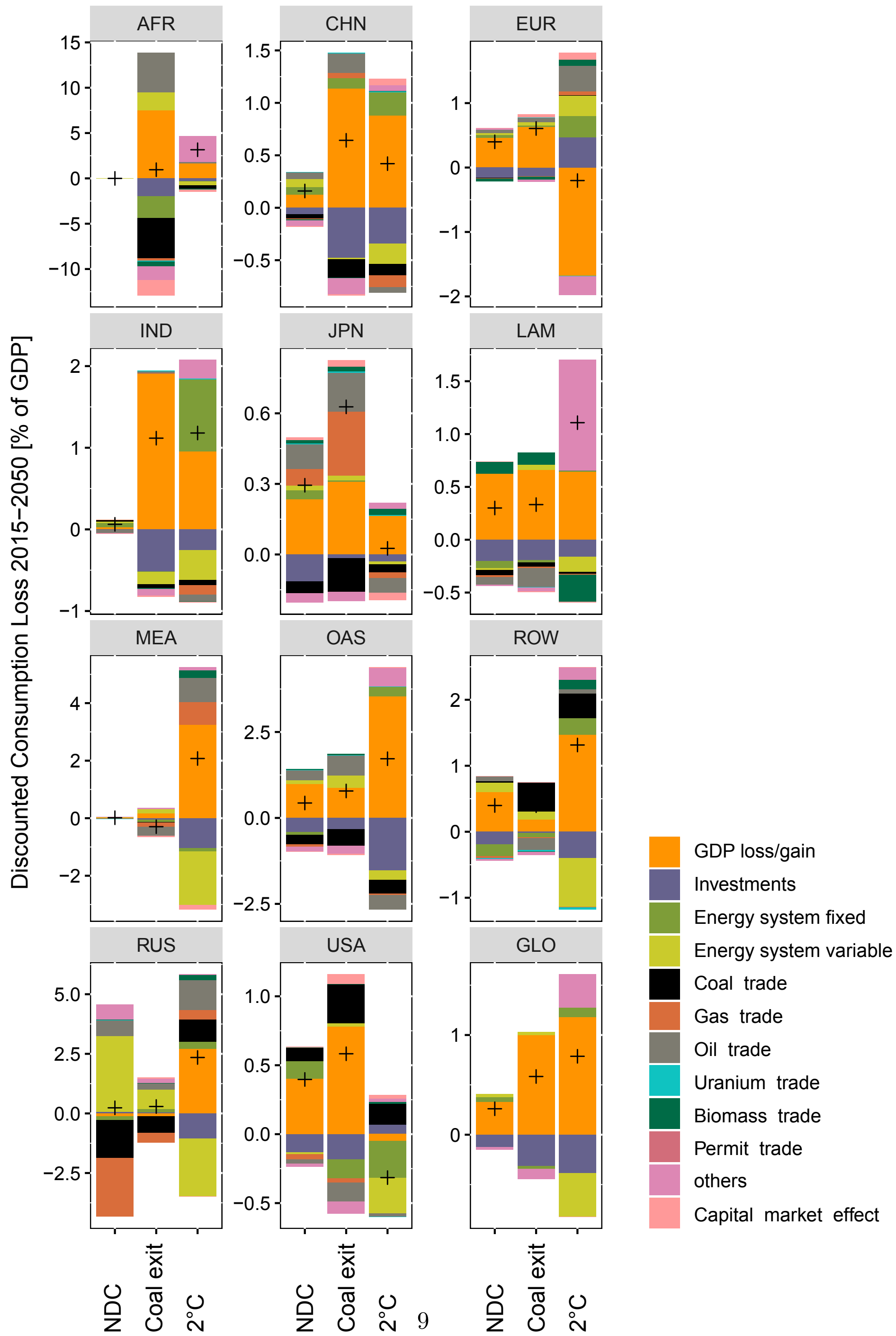


Figure SI-7: |**Decomposition of mitigation cost.** Decomposition of regional mitigation cost until 2050 for the NDC, 2°C and coal exit scenario compared to the Reference case relative to GDP PPP discounted with a rate of 5%.



GDP loss and energy system related investment cost dominate the mitigation cost in the coal exit and 2 °C scenario for India, China and globally. Global cost savings are mostly comprised of lower non-energy investment cost and additionally less variable cost of the energy system in the 2 °C scenario. The impact of exiting coal on consumption is most prominent in coal exporting regions such as the USA and ROW (including Australia) through lower revenues and higher cost for alternative fuel for coal importing regions such as Japan and China.

SI-1.3. Air pollution

We find that exiting coal leads to similar air pollution health impact reductions as the 2°C scenario. The substitution of coal with gas and oil leads to slightly higher emission; however, emission factors for gas decrease substantially in the long term and biomass related air pollution emissions are higher in the 2°C scenario.

Phasing out coal leads to substitution effects, especially gas substitute coal in the power sector and oil, gas and biomass in the industry and buildings sector. However, there are effects that further lower air pollution emissions: India, for example is a fast growing economy that is expected to double its GDP in the next 15 years while continuing the trend of a growing population. This results in a tripling of transport demand from until 2040, which is the major emitter of NOx. In this context, the coal exit significantly increases the oil price compared to the 2°C scenario (22% in 2030), which has a twofold effect leading to lower air pollution emission: 1) The higher price for liquids based final energy reduces the transport demand (37% in 2030) and 2) leads to a substitution of oil with electricity based mobility (65% higher rate of electrification).

Figure SI-8: |**Air pollution concentration.** Global mean annual $PM_{2.5}$ concentration $[\mu g/m^3]$ for the year 2015 and 2050 of the NDC, 2°C and coal exit scenario. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange),

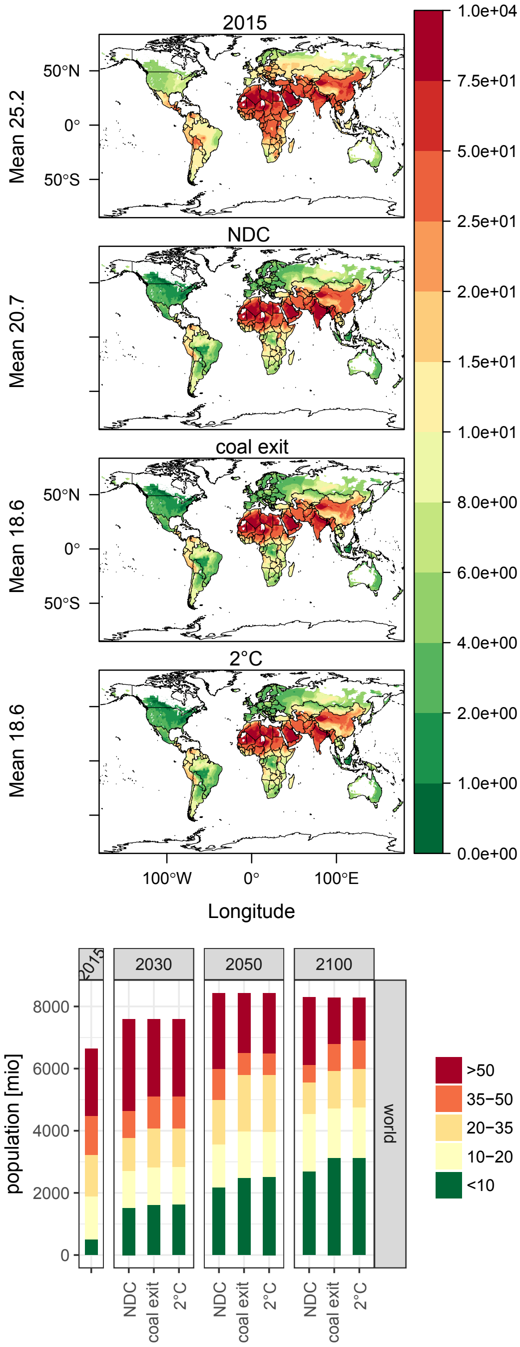


Figure SI-9: |**Air pollution health impact.** Global health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths [$cases/km^2$] for the year 2015 and relative to 2015 for the year 2050 of the NDC, 2°C and coal exit scenario. Markers represent values for stringent (⊗) and fixed emission factor (+) sensitivity cases, see Rauner, S. et al. Air Quality Co-benefits of

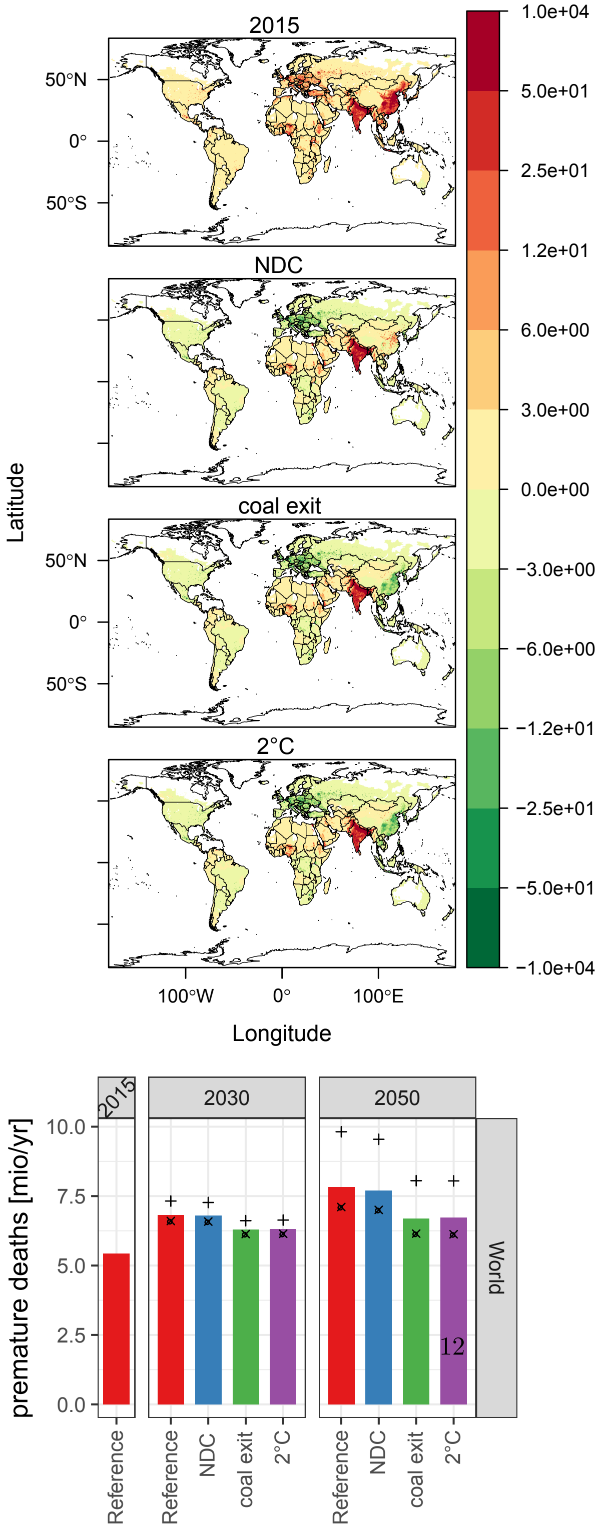


Figure SI-10: |**Air pollution impact on Secondary Energy level [DALY].** Air pollution impact on Secondary Energy level for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050.

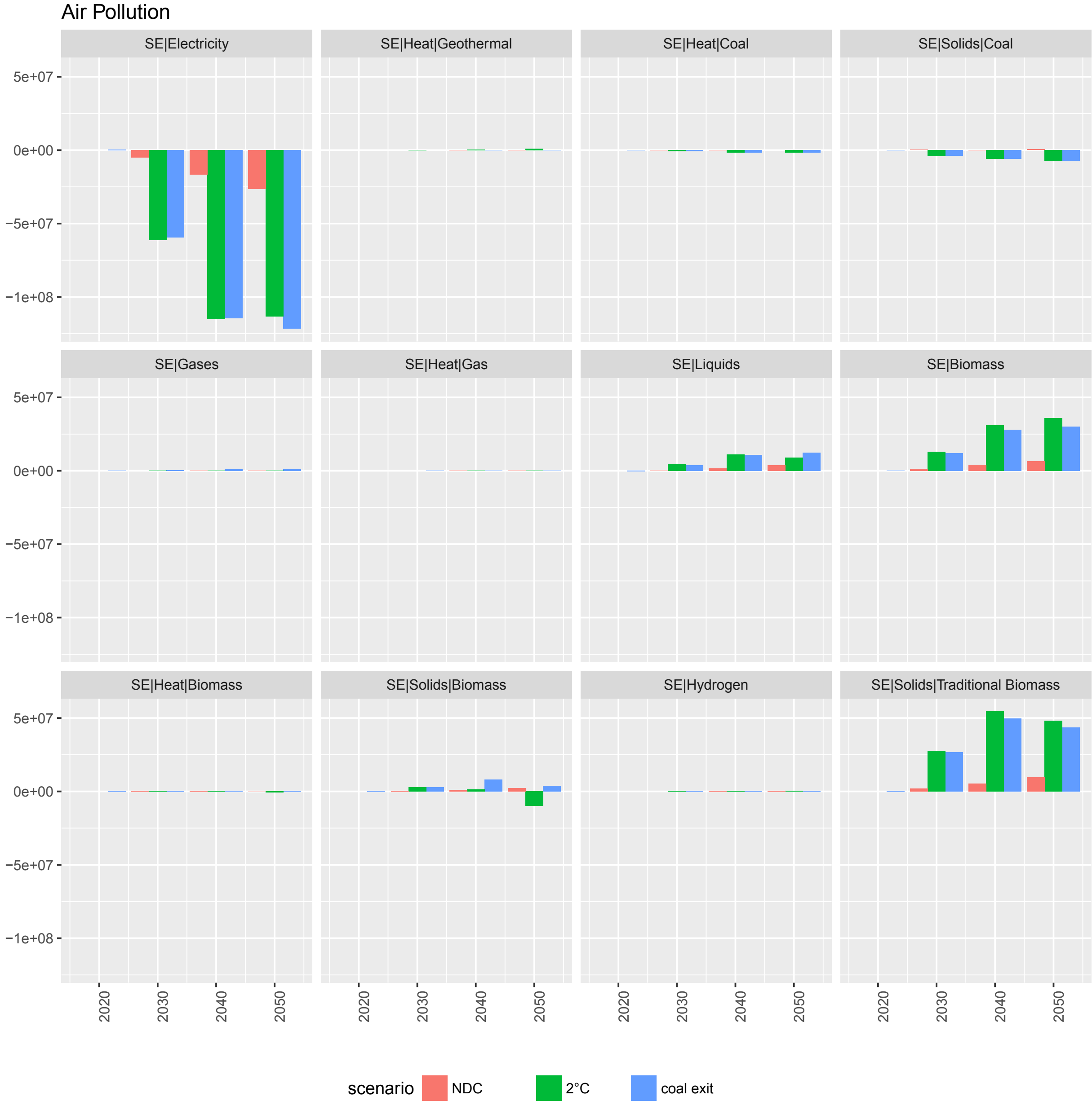
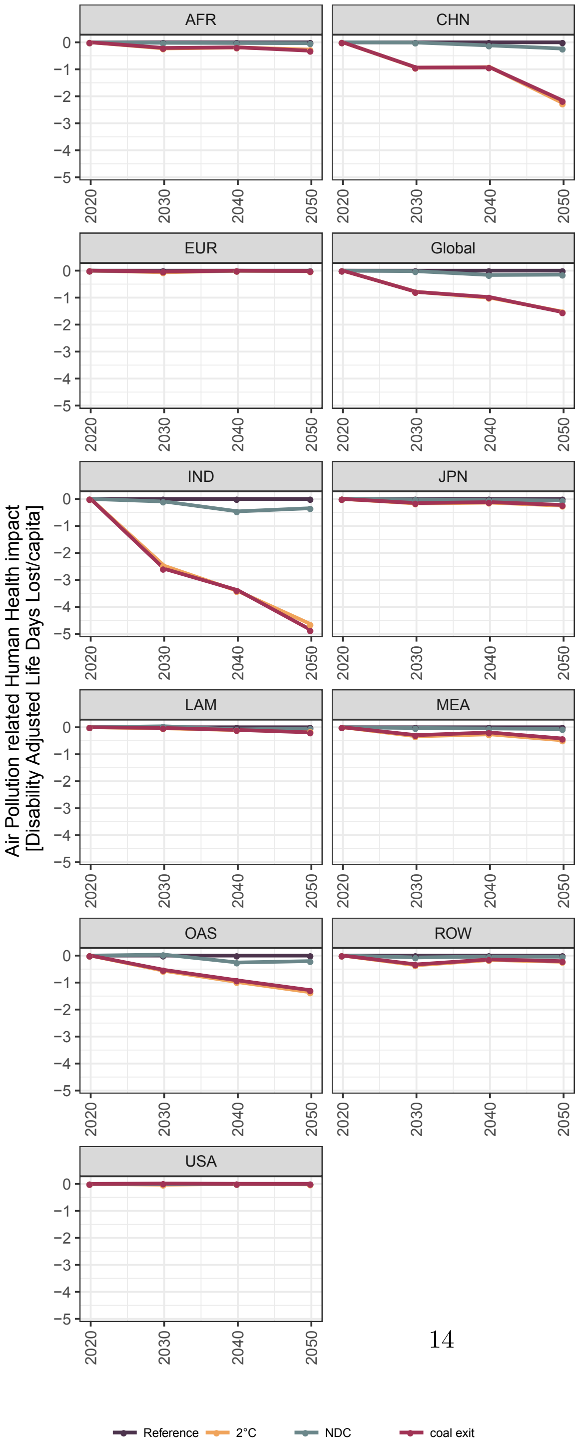


Figure SI-11: |**Regional Air pollution impact [DALY/capita].** Regional Air pollution impact for the Reference, NDC, Coal exit and 2°C scenario until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.



SI-1.4. Life Cycle Assessment

Figure SI-12: |**Total global absolute impacts.** Total global absolute impacts for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

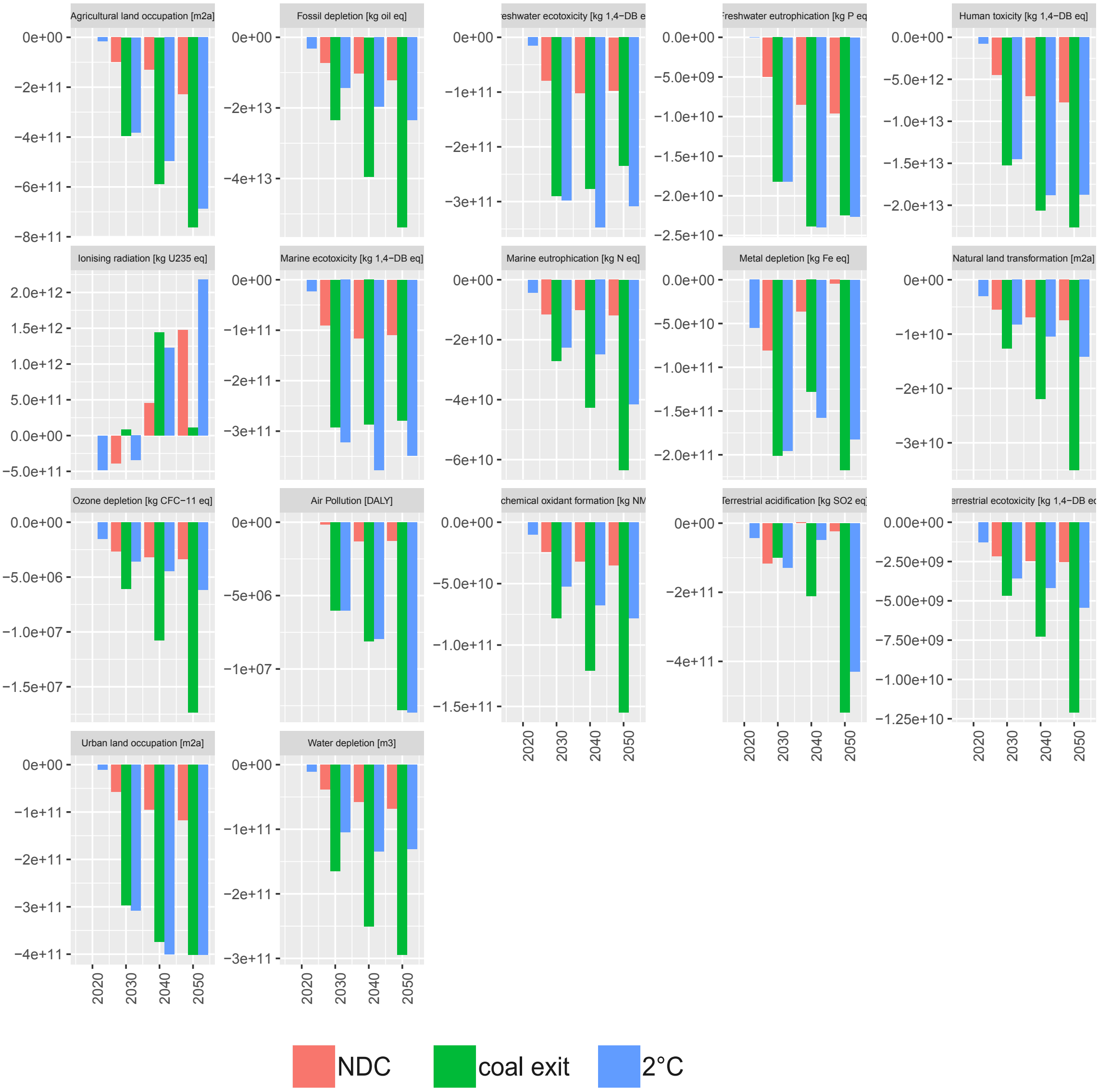


Figure SI-13: |**Global absolute impacts of Secondary Energy - Electricity.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

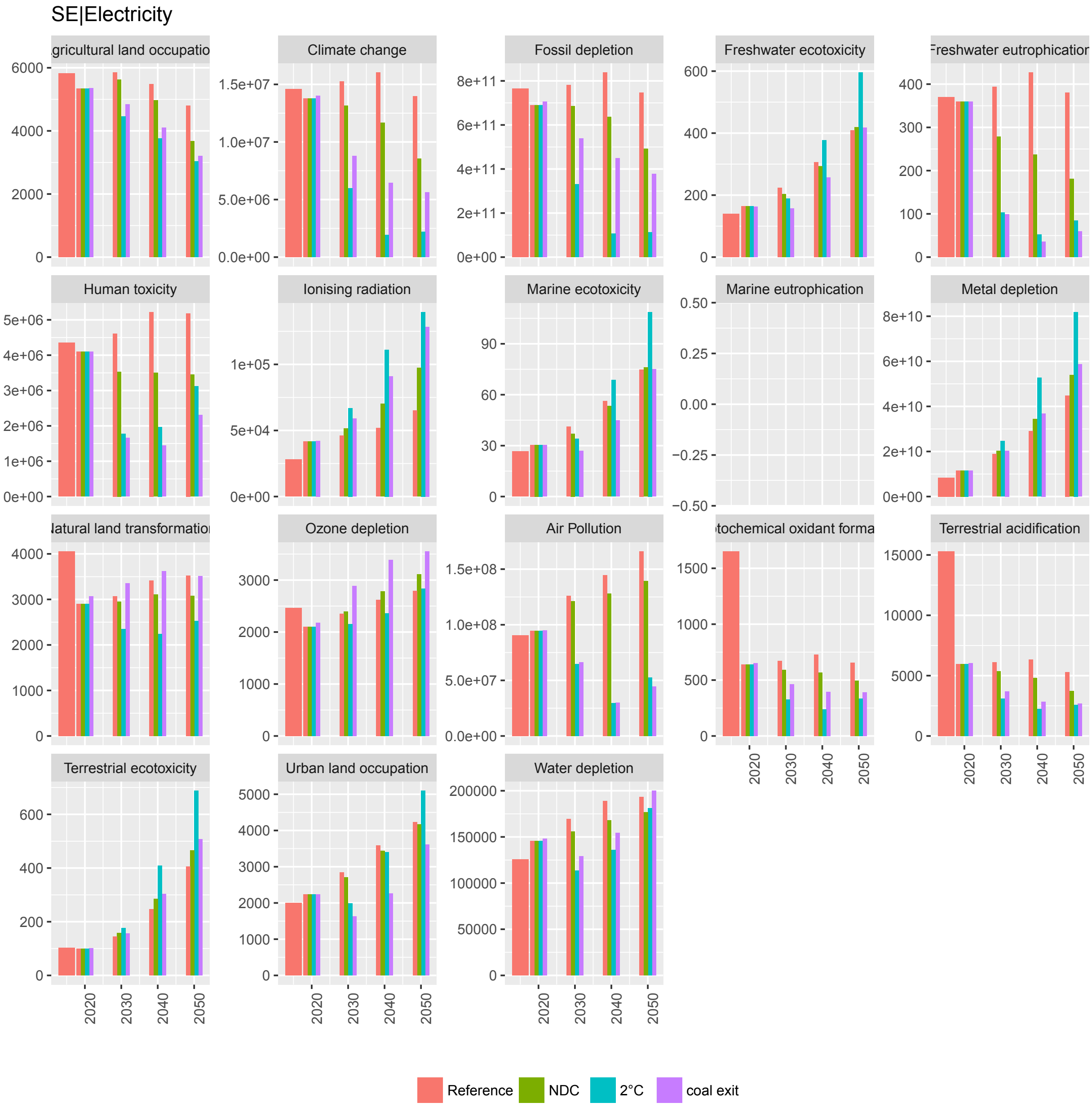


Figure SI-14: |**Global absolute impacts of Secondary Energy - Heat|Geothermal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

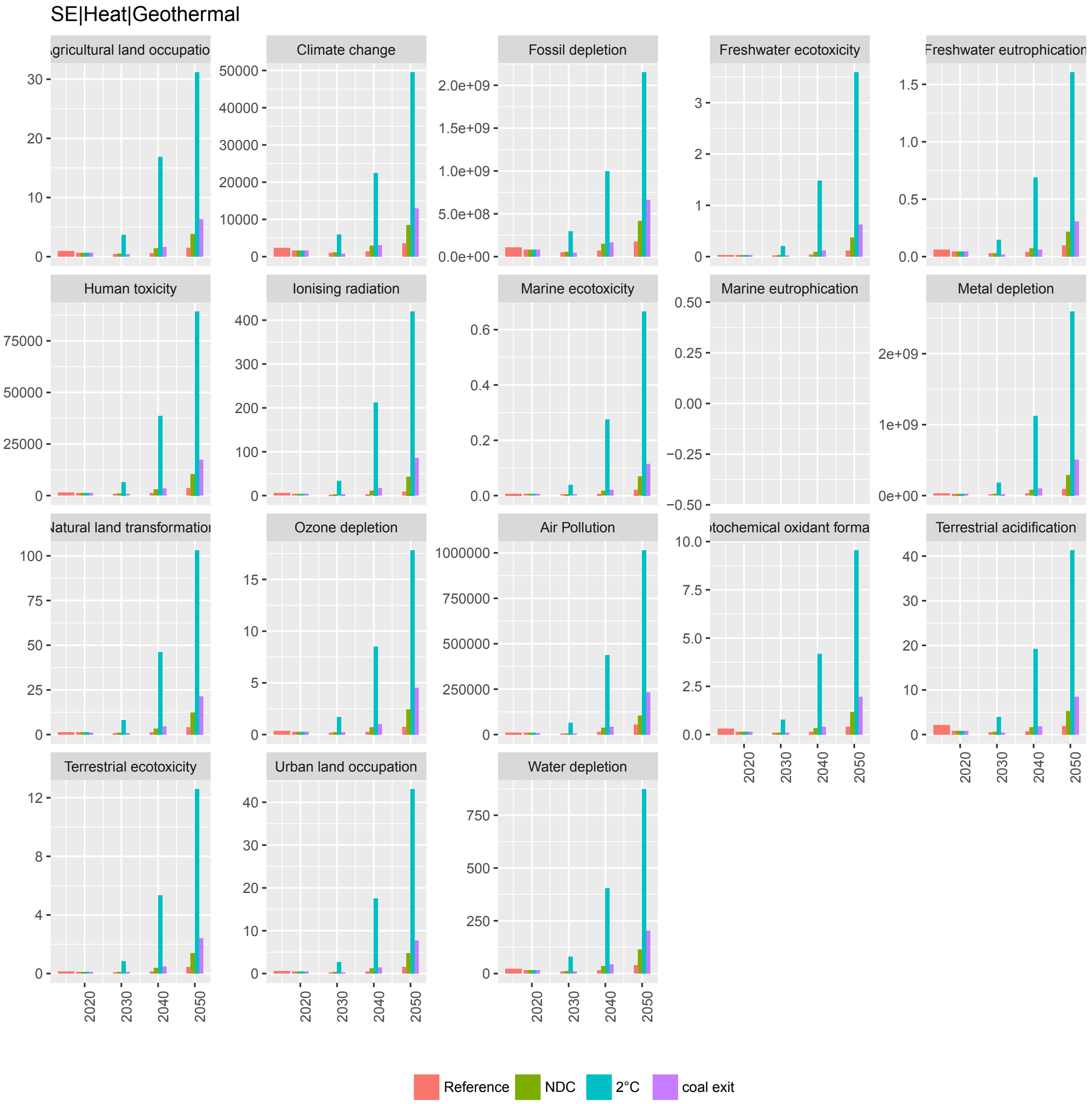


Figure SI-15: |**Global absolute impacts of Secondary Energy - Heat|Coal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

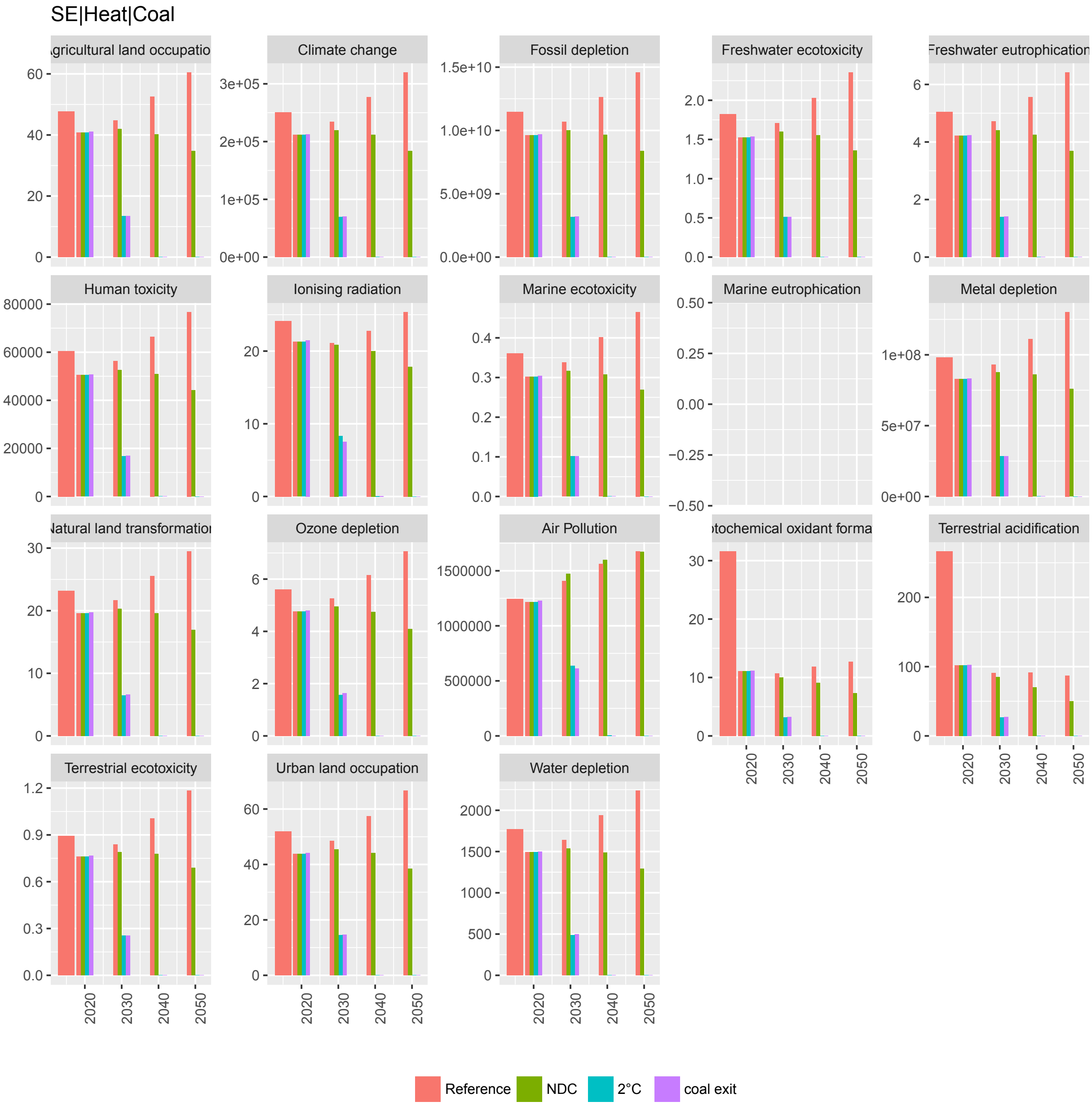


Figure SI-16: |**Global absolute impacts of Secondary Energy - Solids|Coal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

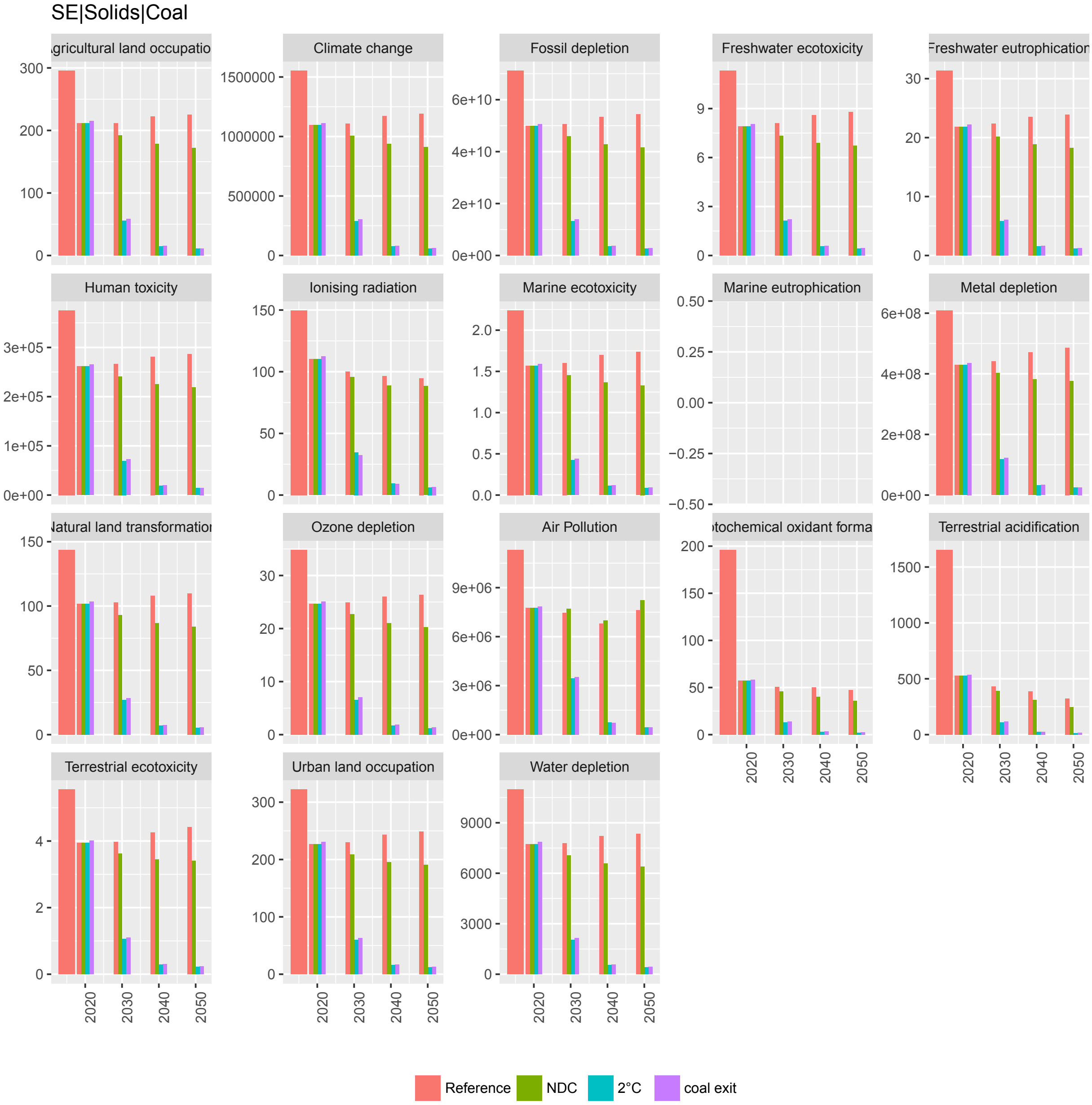


Figure SI-17: |**Global absolute impacts of Secondary Energy - Solids|Gases.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

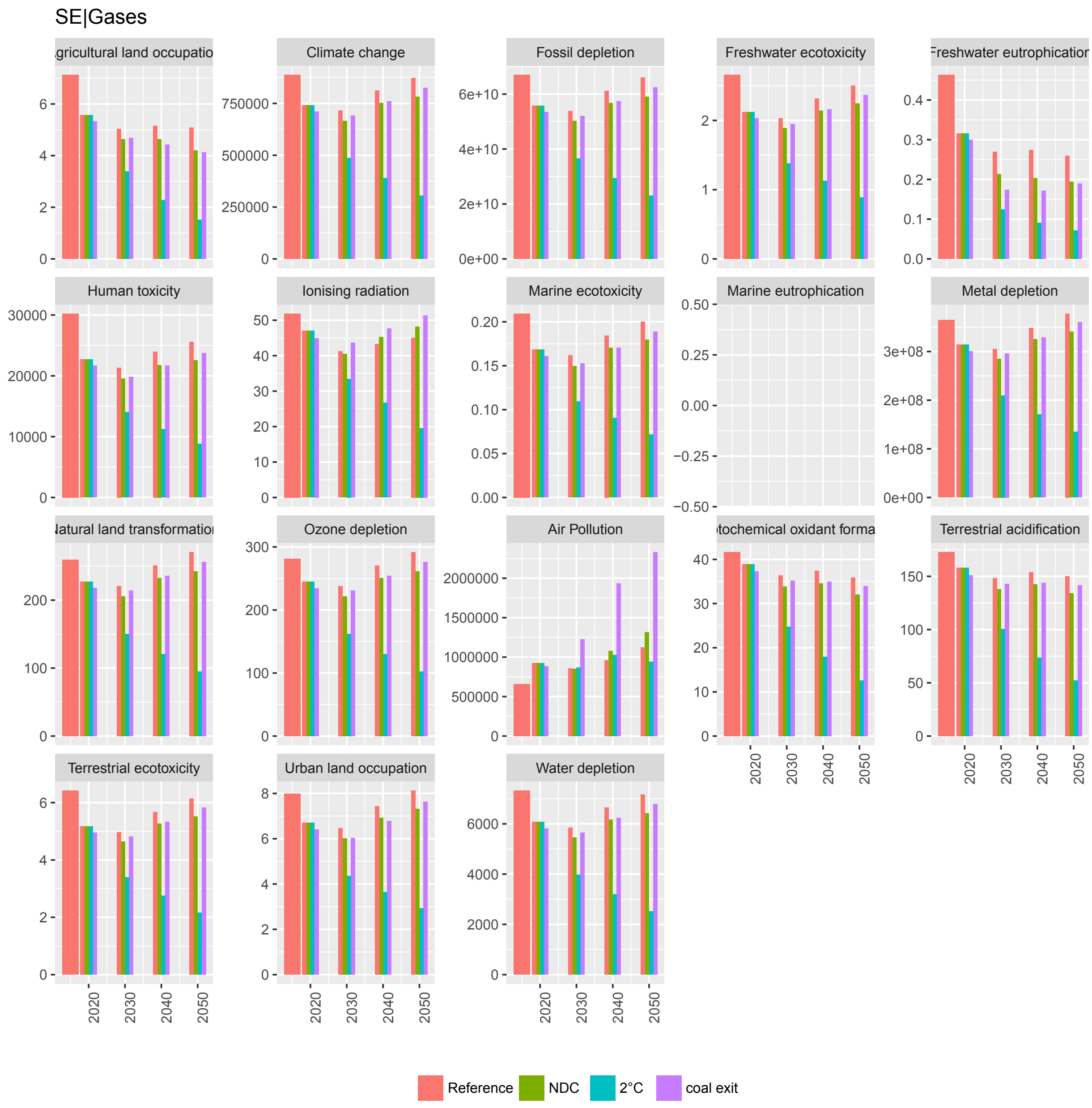


Figure SI-18: |**Global absolute impacts of Secondary Energy - Heat|Gas.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

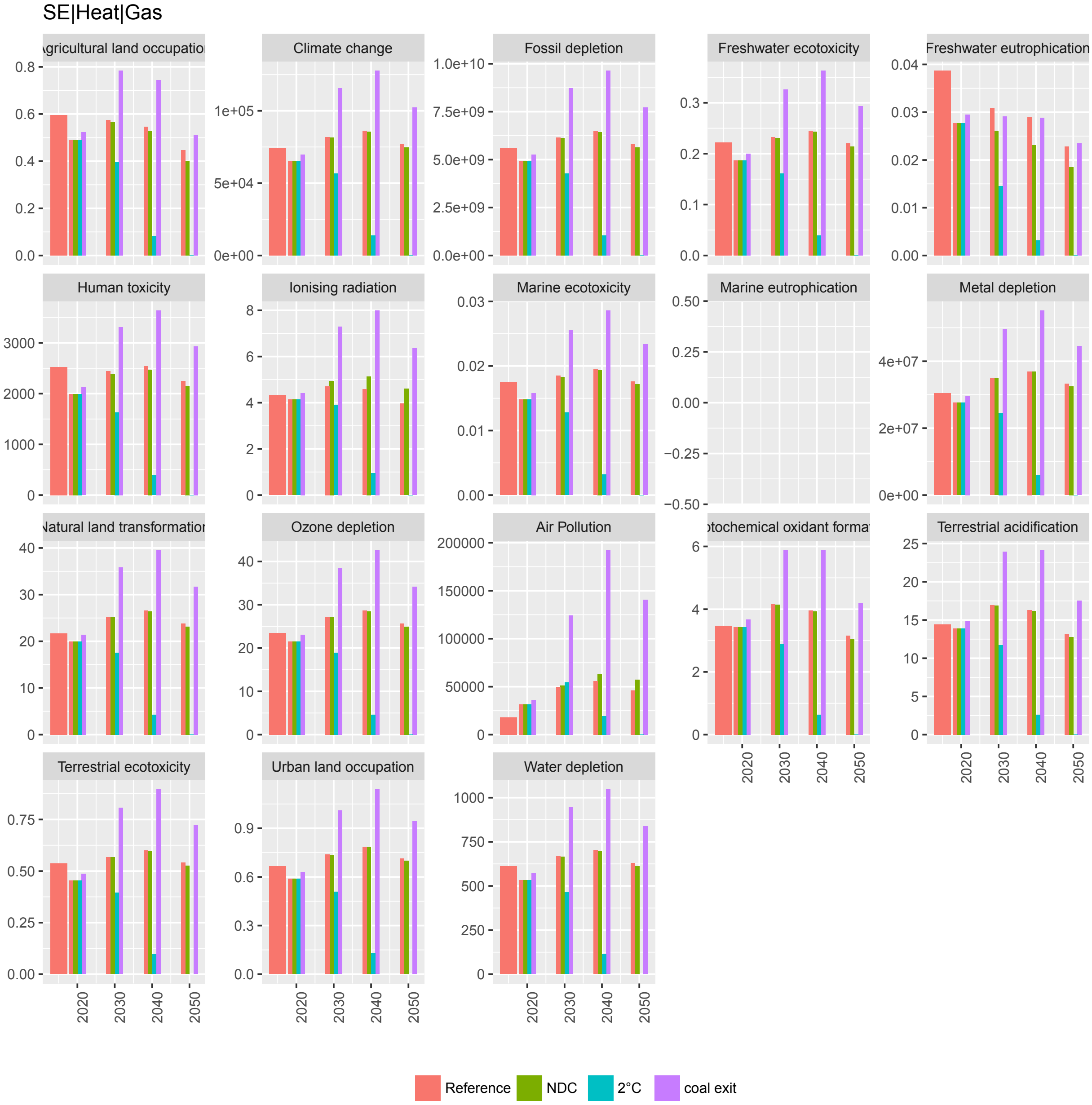


Figure SI-19: |**Global absolute impacts of Secondary Energy - Liquids.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

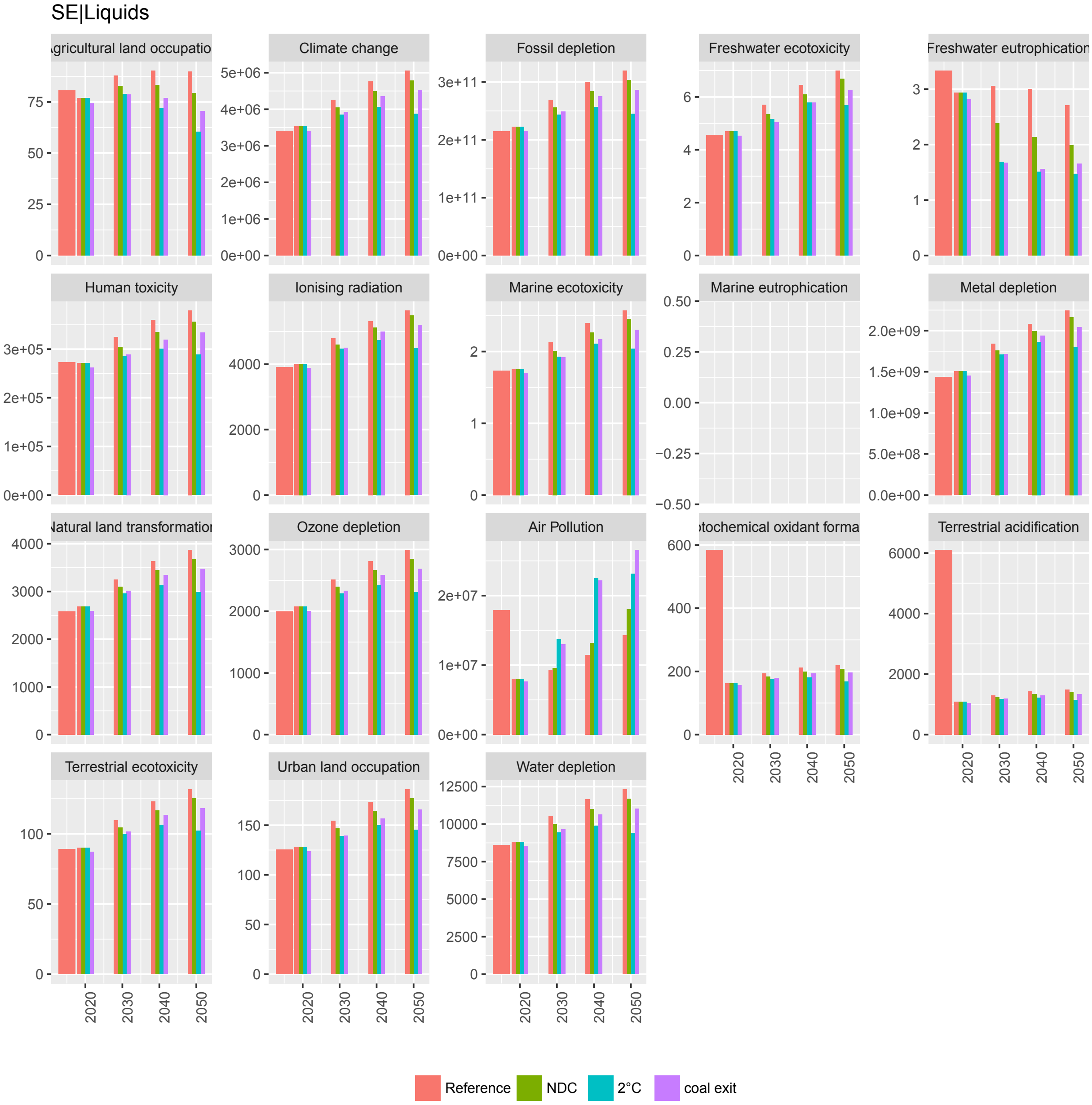


Figure SI-20: |**Global absolute impacts of Secondary Energy - Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

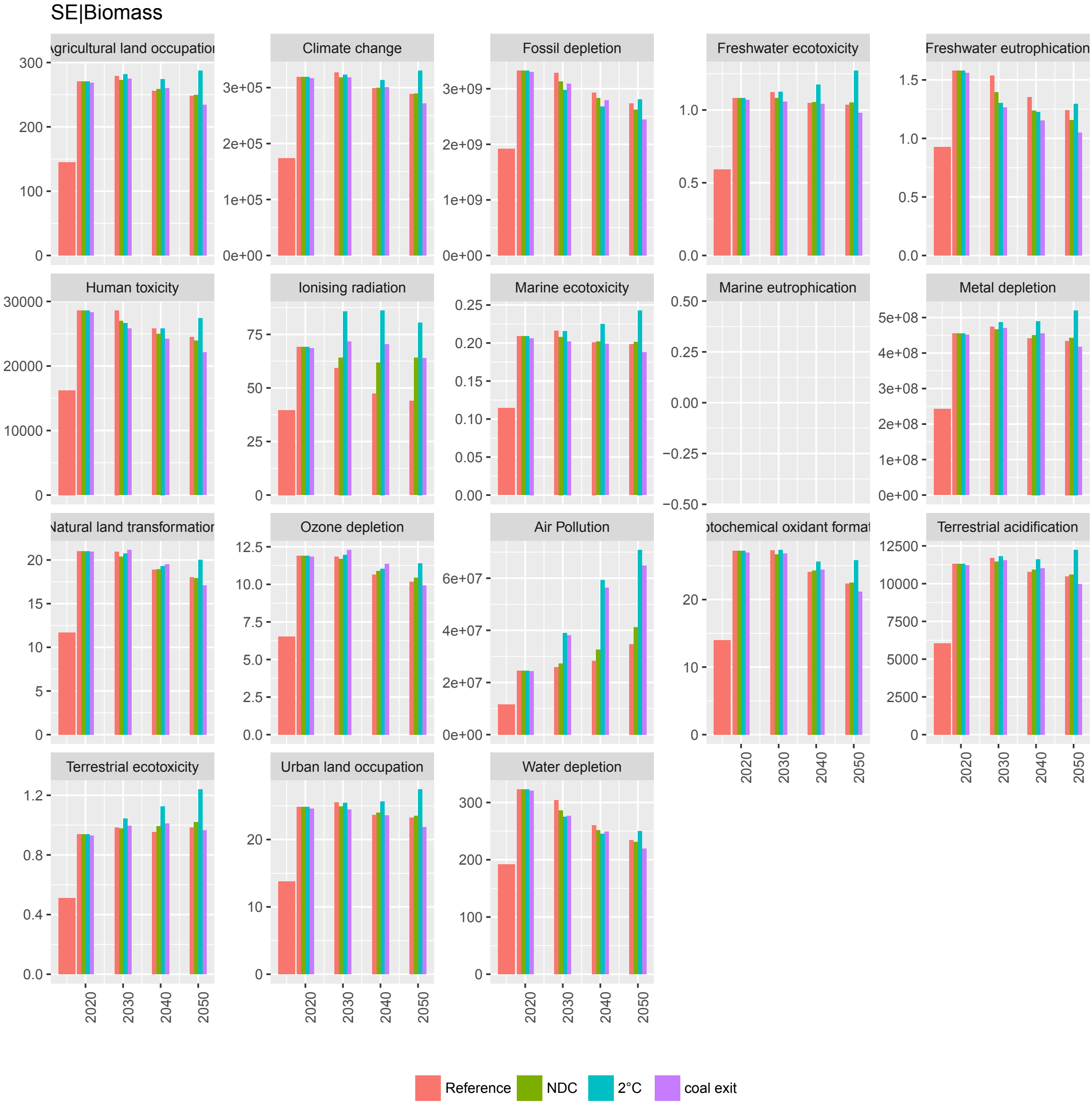


Figure SI-21: |**Global absolute impacts of Secondary Energy - Heat|Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

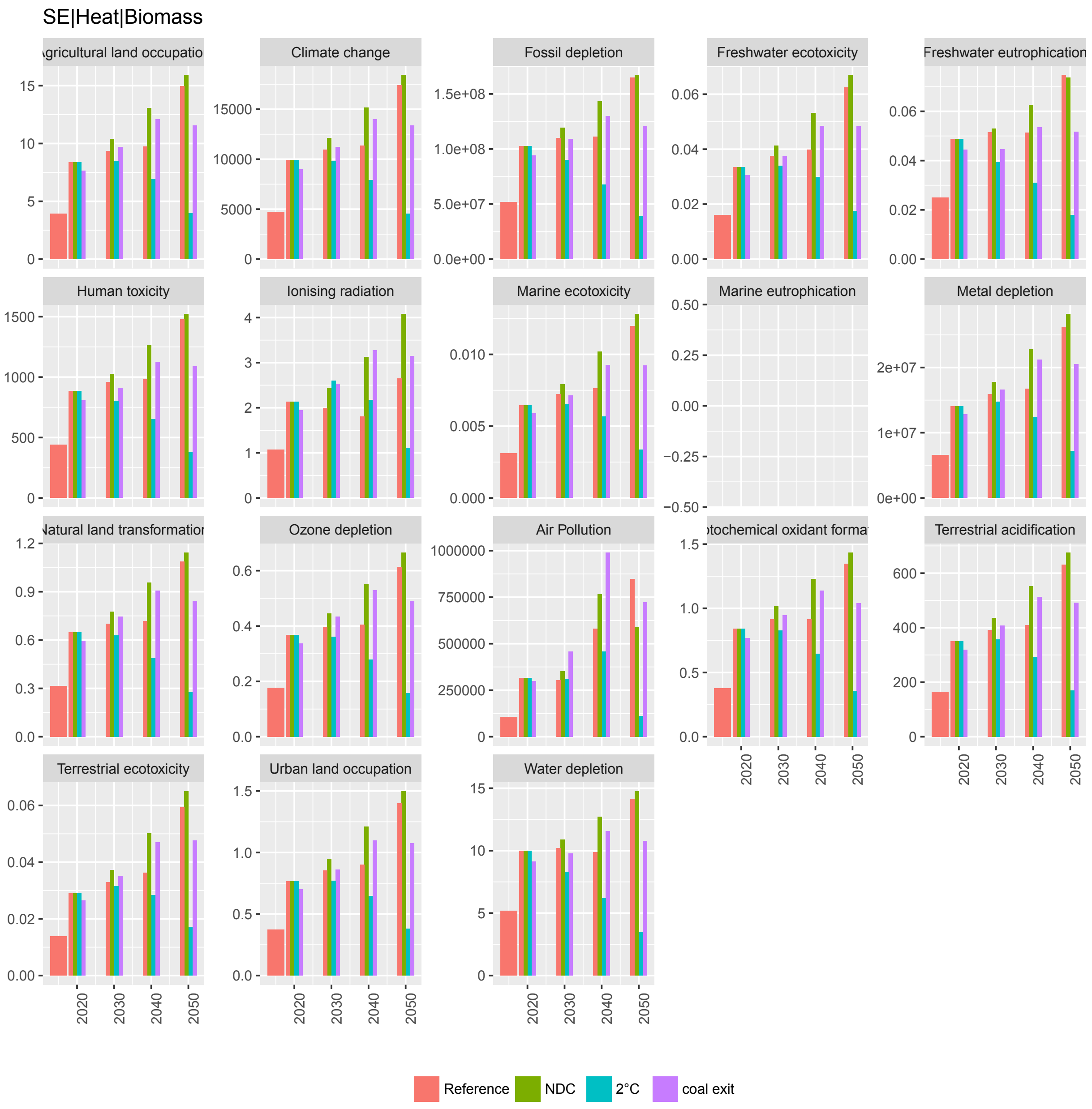


Figure SI-22: |**Global absolute impacts of Secondary Energy - Solids|Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

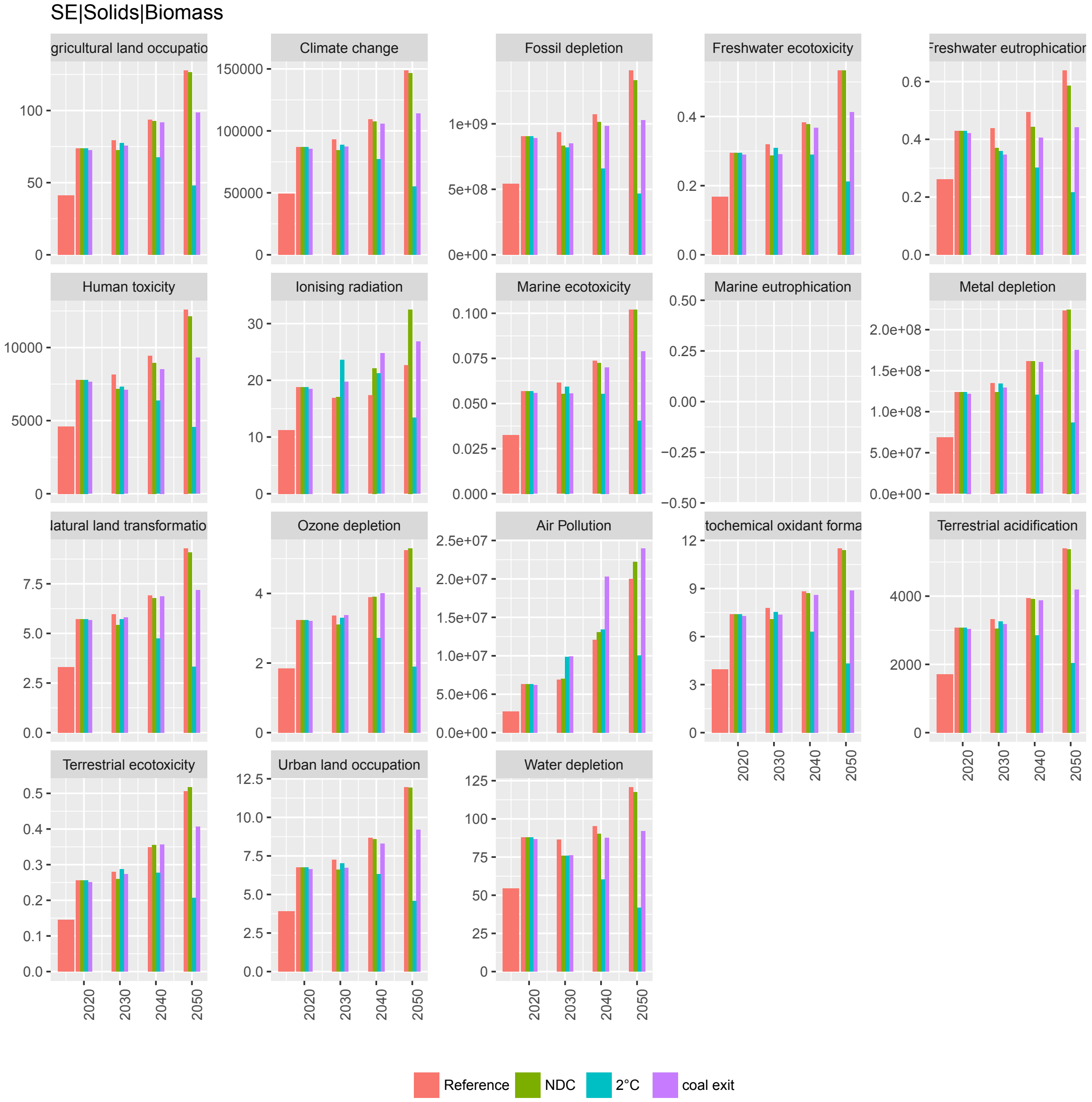


Figure SI-23: |**Global absolute impacts of Secondary Energy - Hydrogen.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

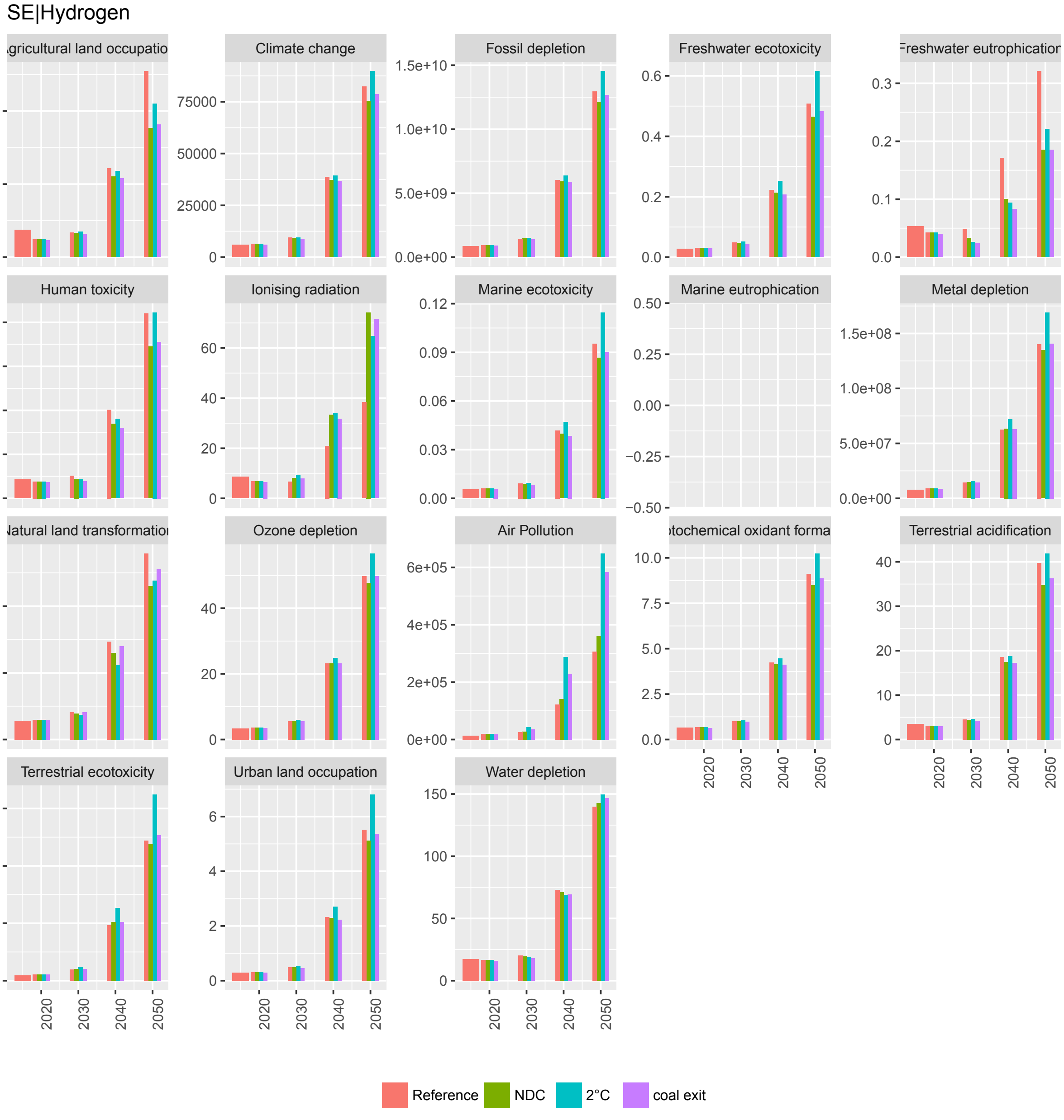


Figure SI-24: |**Global absolute impacts of Secondary Energy - Solids|Traditional Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

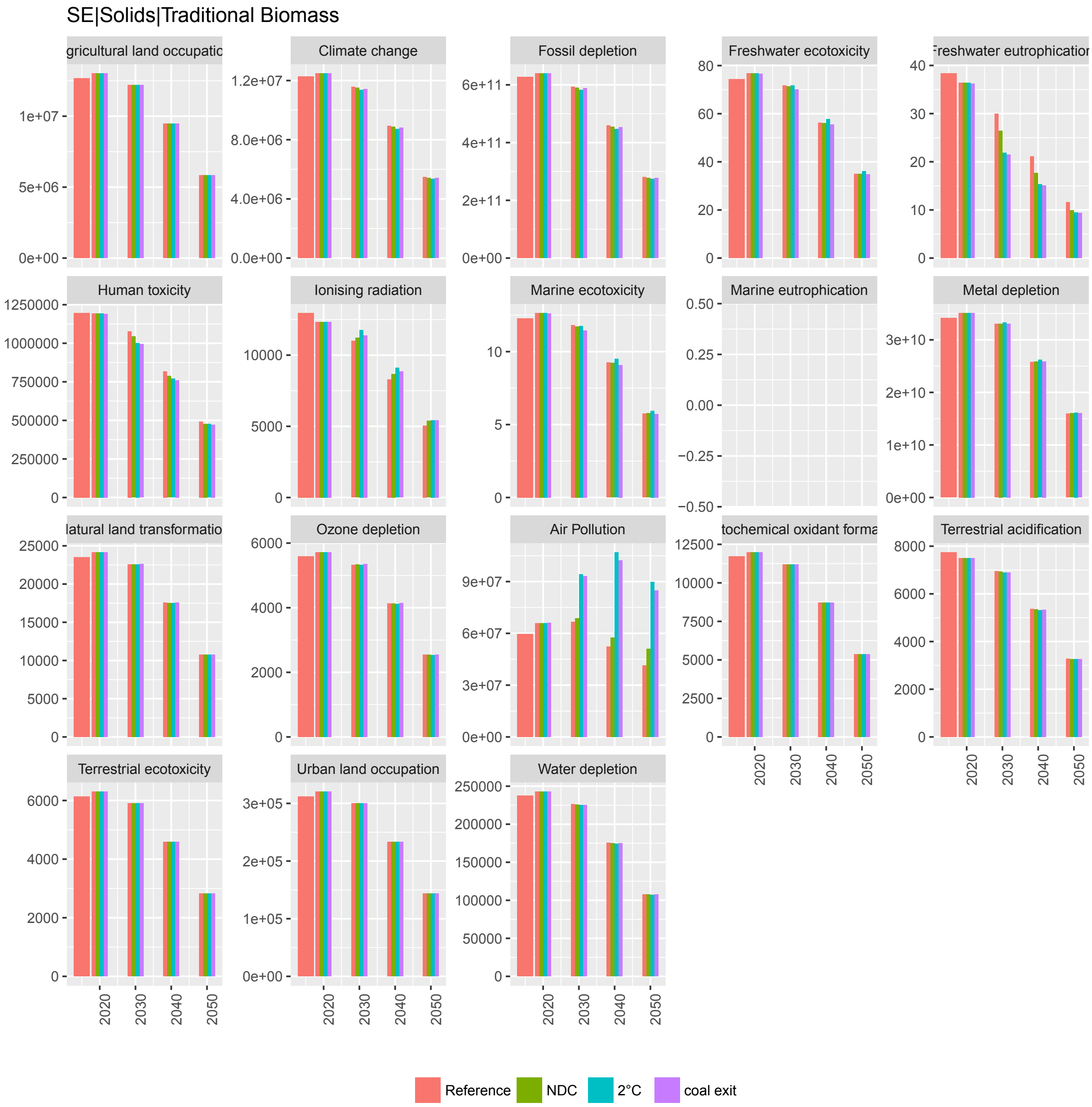


Figure SI-25: |**Global absolute cost of Secondary Energy - Electricity [US$].** Global absolute cost of Secondary Energy - Electricity for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050.

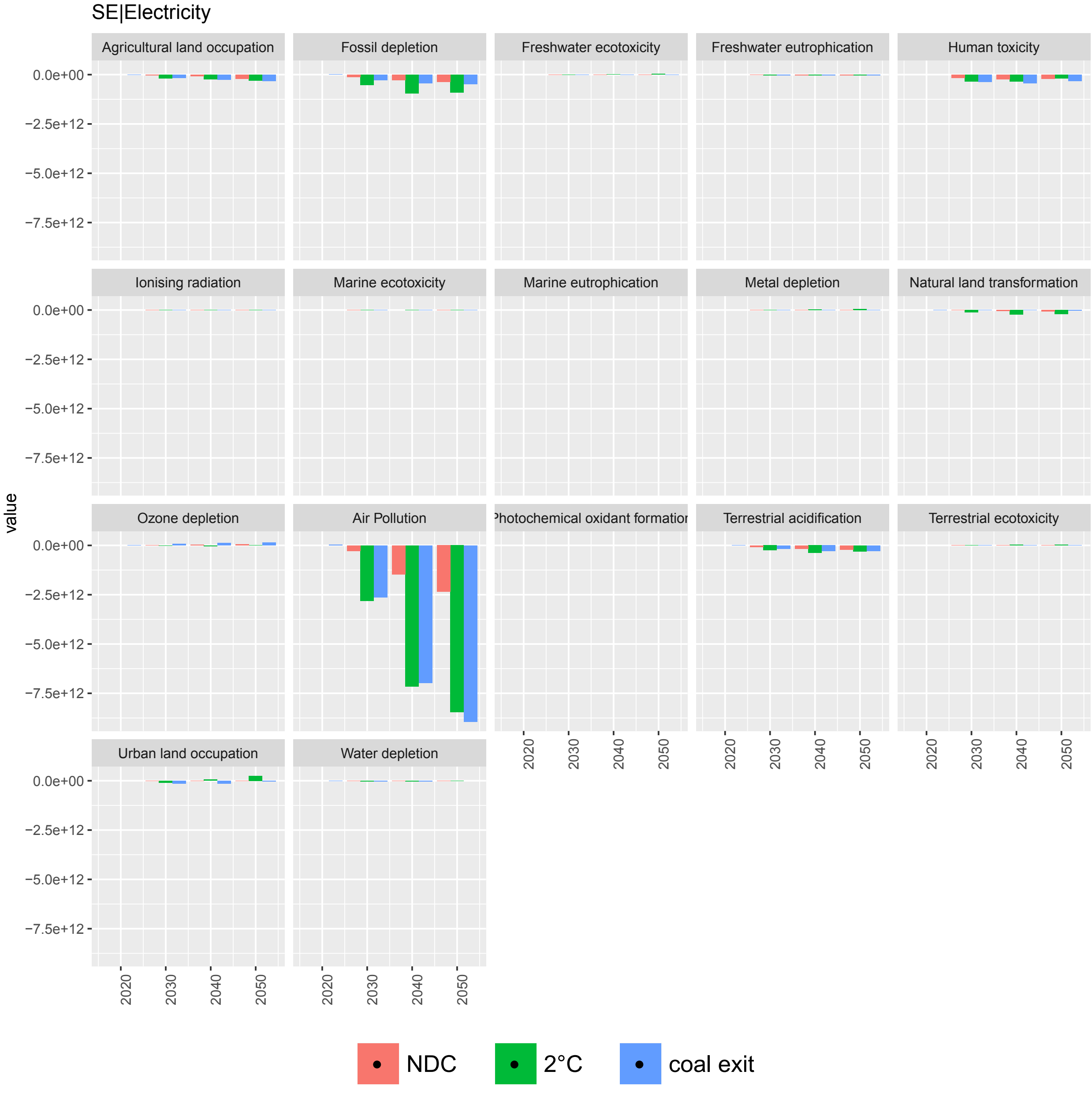


Figure SI-26: |**Regional local monetized impacts as a share of GDP PPP.** Regional local monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-27: |**Regional local monetized impacts.** Regional local monetized impacts for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-28: |**Regional local and global monetized impacts as a share of GDP PPP.** Regional local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

Figure SI-29: |**Global local and global monetized impacts as a share of GDP PPP.** Global local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

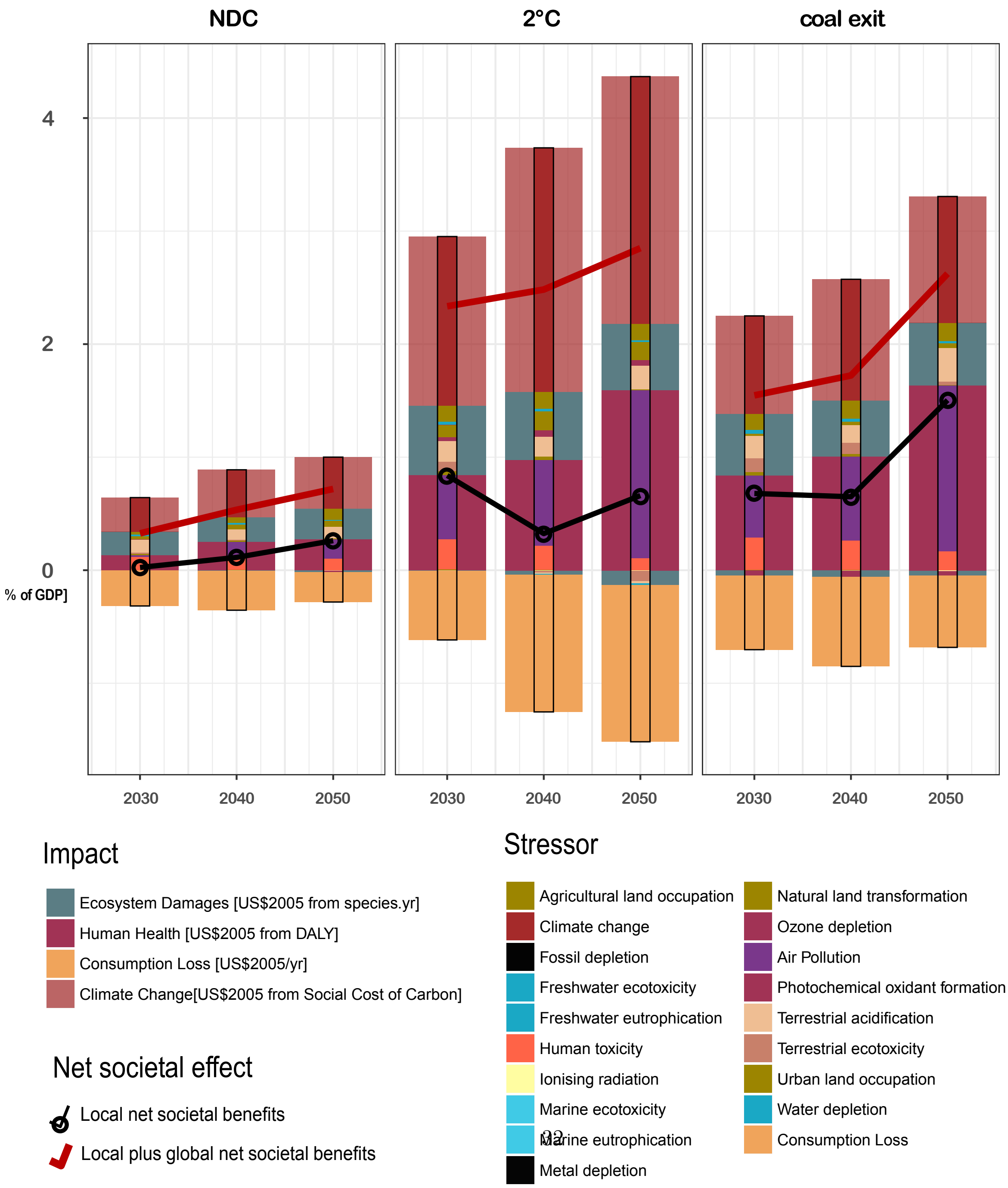


Figure SI-30: |**Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Discounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.

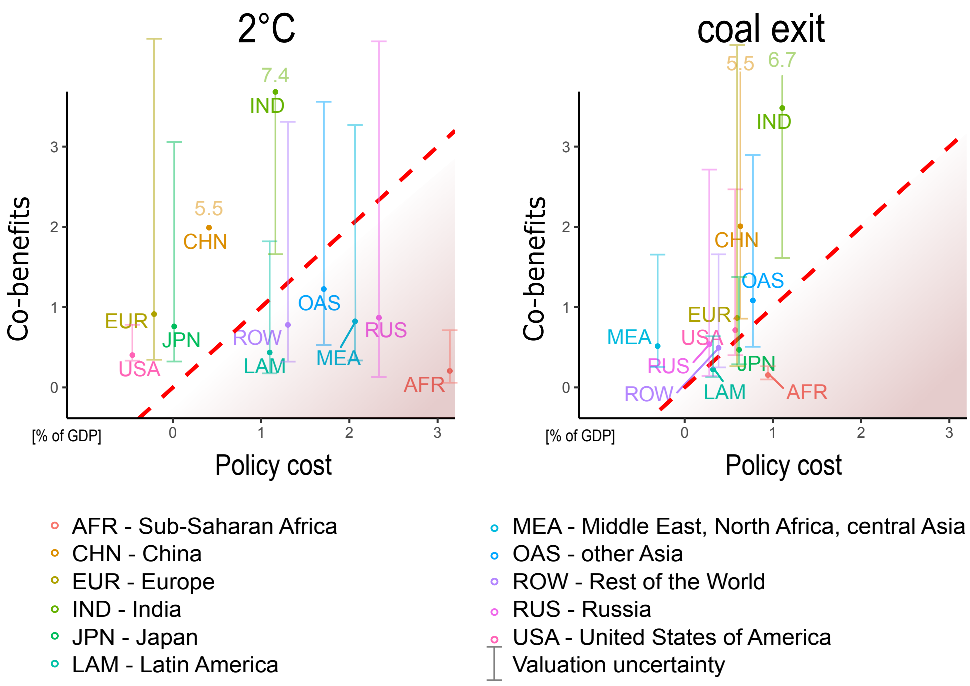


Figure SI-31: |**Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits.

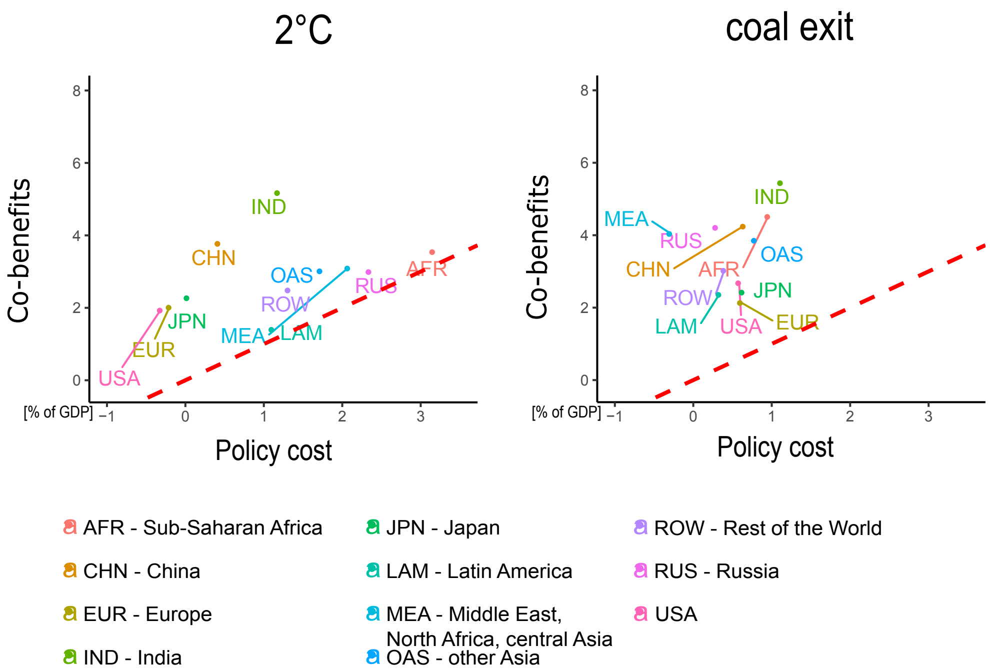


Figure SI-32: |**Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Undiscounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP. The dashed line indicates the break-even between cost and benefits.

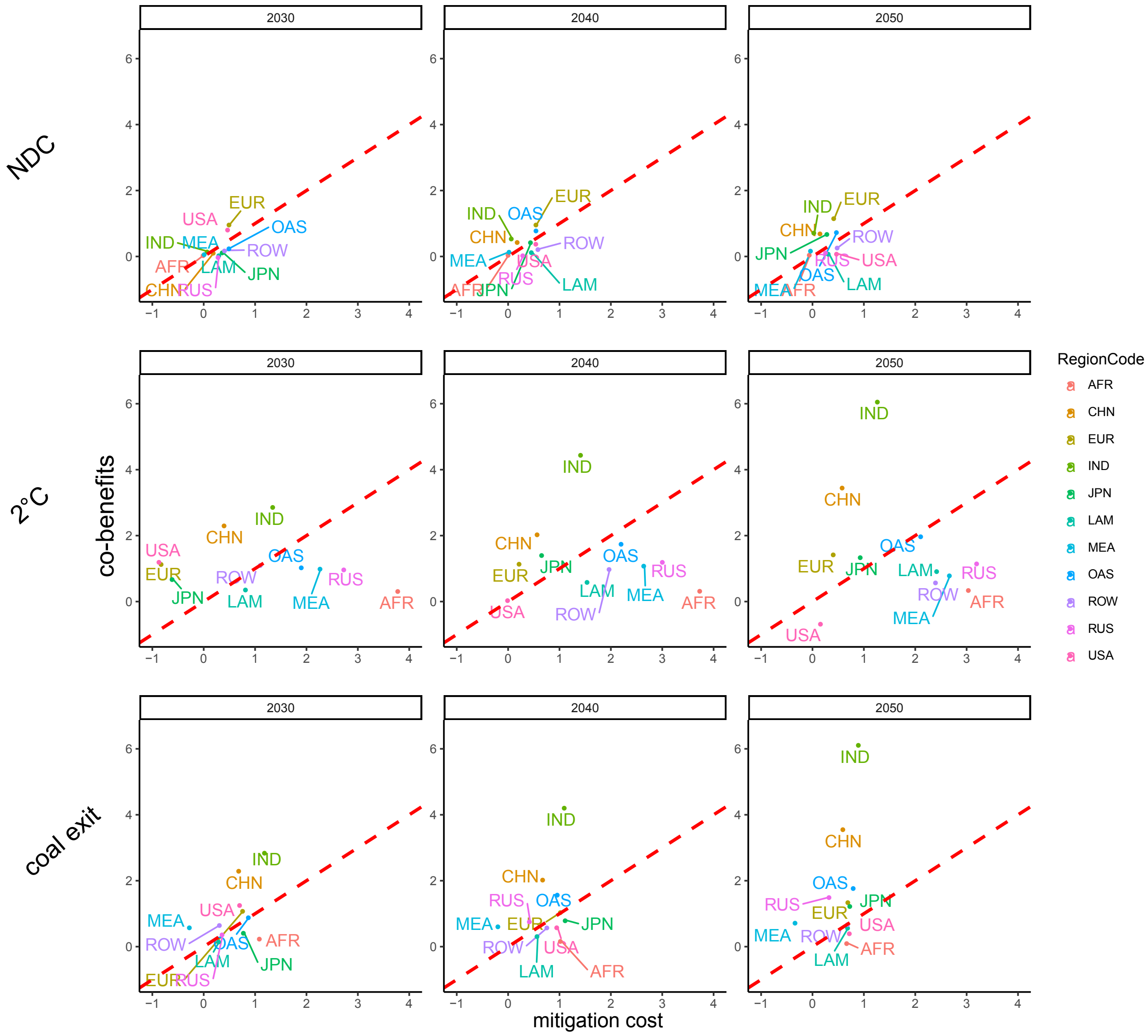
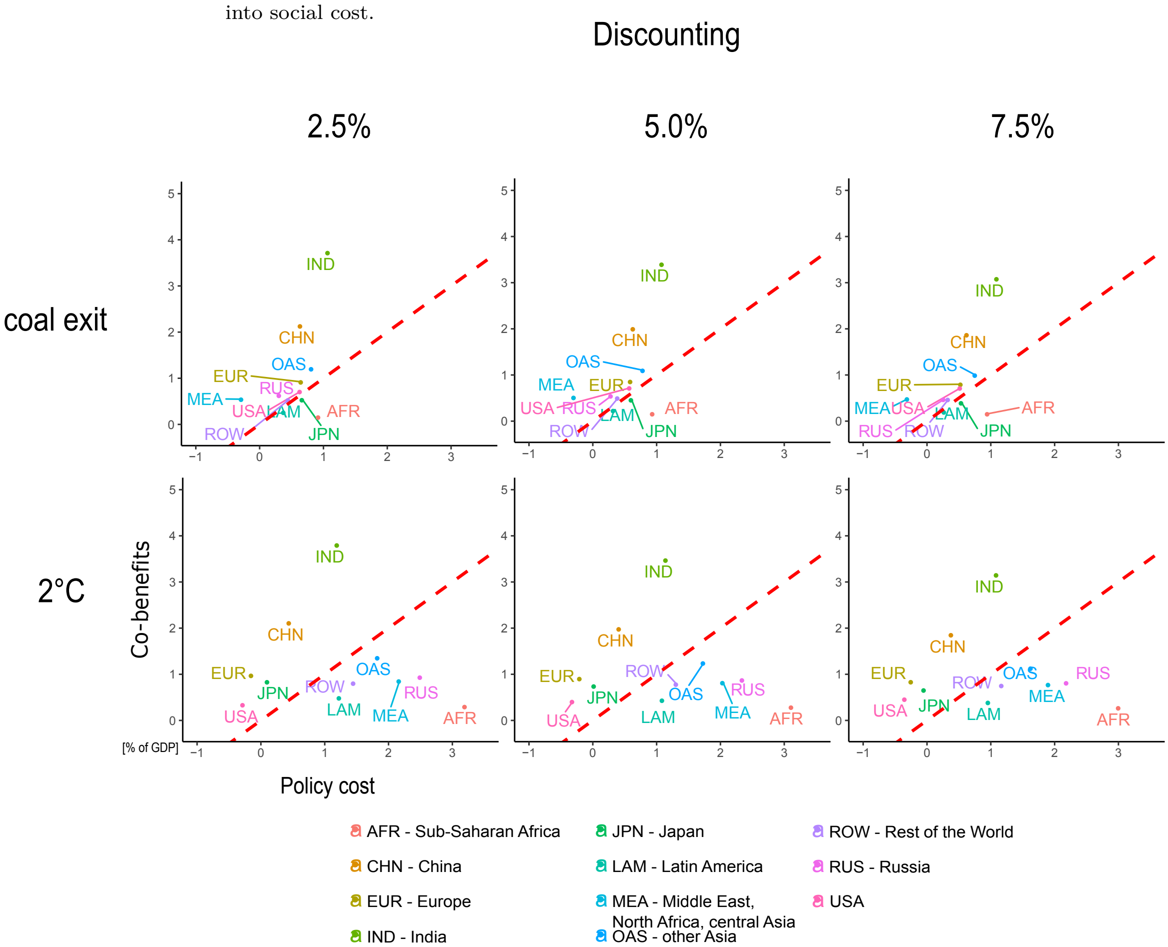


Figure SI-33: |**Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rates of 2.5, 5 and 7.5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.



Chapter 5

Synthesis and Outlook

The main objective of this thesis is to quantify the co-benefits and adverse side effects of climate policy. The main three chapters reflect different foci. The 2nd chapter analyse the co-benefits of climate policies on air quality and compares them to the associated mitigation cost. The focus of the 3rd chapter is on a comprehensive life cycle based assessment of impacts and their inclusion through a multi criteria optimization for a subsystem, the electricity system in Germany. Finally, the 4th chapter describes a comprehensive analysis of different global climate policy scenarios with a focus on the comparison of cost and benefits.

I will first present a synthesis of the major findings of this thesis. In the second part, I will discuss the results and their policy implications. Finally, I will address further research possibilities.

5.1 Synthesis of results

Our research confirms that the current climate policies in place are not suitable to limit global warming to the goal adopted in the Paris Agreement. Nationally Determined Contributions need strengthening since they only achieve limiting the global mean temperature to about 3.5°C by the end of the century. This will require near term and deep mitigation measures affecting all sectors. These climate mitigation policies pose chances and risks for achieving other sustainability goals formulated in the Sustainable Development Goals adopted by the UN.

In chapter 2 we show that ratcheting-up from the NDCs to more stringent climate poli,cy yields considerable co-benefits in terms of avoided air pollution health impacts. Monetizing these co-benefits results in a net benefit (subtracting higher mitigation cost) of 0.08% of global GDP until 2050. Especially the developing regions China and India yield high co-benefits of 1.5% and 0.5% of GDP respectively. We further extended the scenario space through an air pollution policy dimension. This facilitated the analysis of the robustness of co-benefits in terms of different air pollution policy stringency scenarios. Here we find that although assuming stringent air pollution policies lowers the co-benefits of climate policy, the benefits are still positive on a global level. The main result of this chapter is the magnitude of the air pollution benefits; however, it also shows that capturing the full magnitude of air pollution effects requires a specific modeling. The explicit modeling chain, including spatially explicit soci-economic data, showed that India faces a severe air pollution crisis even with decreasing emission caused by an expected tripling of population over 30 years of age, progressing urbanization and high economic growth. We further show that strengthening climate policy not necessarily lowers emissions from sectors such as transport and industry, capturing these effects require a system wide analysis.

In chapter 3, we show that renewable energies not only emit the lowest GHG they also outperform fossil fuel based technologies on most of the other sustainability criteria. We further show that the co-benefit consideration needs to be comprehensive as climate policies can lead to challenges in land-use and resource depletion that need further attention. Another result of the spatial contribution analysis is that including the whole life cycle and a system wide analysis are crucial as impacts are shifted from direct to indirect emissions and unintended substitution effects need to be accounted for. Calculating the Pareto-front of efficient solutions of system cost and sustainability impact for the German electricity system shows that the trade-off between cost and impacts are non-linear. This emphasises the need to move from the ex-post assessment of policies and transition pathways to including the sustainability consideration into the optimization of the pathways itself. This would reveal the optimal pathways considering not only climate mitigation but also other sustainability implications.

Our main result of chapter 4 is that when applying a comprehensive prospective life cycle assessment base analysis, the local co-benefits of climate policy alone are in the same order of magnitude as the mitigation cost. We confirm that pollution caused human health impacts are the major contributor of the overall externality of the energy system. However, applying a comprehensive assessment that also includes environmental damages shows that they contribute considerably to the overall impact.

We further show that especially major emitters of GHG emissions such as India and China benefit the most from climate mitigation efforts. In contrast to climate policies, these human health and environmental co-benefits are local and intra-generational. This also makes them less sensitive to intrest rate assumptions compared to climate impacts. As a result, the identification of a global coal exit in chapter 4 as a no-regret strategy for most of the regions can help tackle the described Tragedy of the Global Commons. However, we find that while the coal exit is a crucial early entry point, it needs to be complemented by further climate policies to reach a Paris Agreement compliant temperature goal and to avoid the lock-in of other fossil fuels, especially gas. When we further extend our analysis to also include the damages of climate change the societal benefits of mitigation action further increase. Therefore, exiting coal can only be a first early entry point and further policies tackling the electrification of mobility and resource efficiency need to flank this policy.

5.2 Discussion and policy implications

As stated in chapter 4, our result that a comprehensive analysis of co-benefits and adverse side effects can identify no-regret policies like the coal exit have significant bearing for international climate policy. Exiting coal not only achieves a big step towards closing the emission gap but also compensates mitigation cost through reduced human health and biodiversity impacts, even neglecting reduced impacts from climate change. We further find that the environmental and human health co-benefits of all examined climate policy scenarios (2 °C, coal exit) are in the same order of magnitude as the mitigation cost. As such, they can play an important role to overcome the inter-regional and inter-generational free-rider problem of climate policy, creating an incentive to act even if others do not.

In addition, the local co-benefits can foster public acceptance and the identification of robust no-regret strategies can support local groups in their argument for the introduction or strengthening of climate policies - an important part of the puzzle to overcome known issues of political economy.

Besides quantifying the externalities of the energy system and co-benefits of policies, a key question is how to integrated them into policy design and decision making. In this thesis I explored the multi-objective and ex-post assessment of scenarios approaches. The ex-post approach has the advantage that climate optimal solutions can be assessed on their environmental performance and possible real world policies can be analysed. However, the ex-post analysis does not guarantee overall cost optimally when considering sustainability impacts.

The multi-objective approach avoids monetizing all externalities and makes the trade-offs explicit. Nevertheless it requires aggregating the externalities to one indicator to facilitate the analysis in a two dimensional solution space. More indicators would require more computational power and make the analysis of the Pareto-front in a multi-dimensional space a challenging task.

There are two solutions to these drawbacks. First is a monetization of all externalities and their integration as Pigovian tax. This would guarantee that we calculate welfare optimal solutions given a certain GHG budget, considering not only economic cost but also environmental and human health externalities. However, the challenges of monetizing these impacts remain, which requires value judgments and the monetization of only hard to value features. The second solution is constraining certain sustainability indicators while still optimizing cost, which is an extension of the guard rail approach of climate policy. However, defining boundaries for different sustainability indicators is a challenging task.

Challenges remain but considering externalities is crucial and future research should support the public to have informed discussion about the desirable futures and stakeholders to take informed decisions. Questions remains how to operationalize these results. We identified exiting coal as a no-regret strategy, identifying more of these strategies would facilitate decision makers to implement policies without cost-benefit analysis where a quantification of all impacts is a difficult task. These strategies might include accelerated energy efficiency, electrification of mobility and limiting animal based nutrition.

As elaborated upon in detail in the 4th paper, the applied modeling frameworks are subject to various uncertainties embodied in every step of the modeling chain, from economy-energy-climate modeling to impact quantification and monetary valuation. On the economy-energy-climate model side uncertainties mainly concern the parameter assumptions such as technology cost, renewable energy potentials, technological learning and scale-up rates as well as socio-economic developments.

For air pollution, we are able to model the cause effect chain of emissions, concentrations and human health impacts spatially explicit. However, we do not include other effects than mortality and morbidity of air pollution. For example, research points towards a considerable effect on labour productivity (1). We additionally only consider health impacts on morbidity and mortality but not on cognitive performance (4), infant mortality (2) and impacts on brain health (3). Our results can therefore be seen as a lower estimate of the overall impact.

On the life cycle assessment modeling side the main uncertainty lies in difficult attribution of emissions, the consistent coupling with the integrated assessment model system and the simplified static impact models. A relatively high uncertainty is introduced by the monetary valuation of impacts, especially the valuation of environmental impacts. Another source of uncertainty is how much human health and environmental damages would affect the economy. We only value these impacts but do not implement a feedback.

5.3 Outlook

Our work points towards four fields where future research should be directed to. Firstly, the above mentioned uncertainty should be reduced and future research should investigate the environmental impact modeling and its monetary valuation in more detail. Especially the consistent coupling of life cycle assessment and energy-economy-climate models needs future research attention from both, the energy system modeling and the industrial ecology communities. Chapter 4 is the first scientific effort to couple all sectors of an energy-economy-climate model with a prospective life cycle assessment approach. This required many simplifications especially in the non-electricity sector and future research is necessary on how to strengthen this coupling.

Secondly, in our work, we rely on the metric of social cost derived from willingness-to-pay approaches for human health and restoration cost for environmental damages. However, there is currently no feedback of human health and environmental quality on GDP. Studies show a considerable effect of pollution on labor productivity in low and high skilled jobs. It would therefore be interesting to couple our work with models of environmental pollution on the economy. However, attribution is difficult which might a cause for delayed action: Higher numbers of air pollution related disease are hard to pinpoint to a specific source, cost are therefore hidden in medical expenditures of health insurance companies and it is not feasible for individuals to just buy clean air for themselves as suggested by the willingness-to-pay approach. This research can help by highlighting that exiting coal is a no-regret strategy but future research should elucidate this field more.

Thirdly, besides our work on air pollution, more explicit models should be added to the modeling chain to make it more meaningful for the problematic fields we identified such as resources, bio-energy, transportation and eutrophication. More effort should be devoted to developing standardized interfaces between the integrated assessment community to the industrial ecology and environmental assessment communities. We contribute to this by making our models and data open-source.

The fourth field of future research need is how to strengthen the integration of the impact assessment into the modeling of transition pathways. This would reveal how optimal transition pathways would look like considering a broad set of externalities and show the sustainability trade-offs between different climate and energy policies.

Bibliography

[1] Jiaxiu He, Haoming Liu, and Alberto Salvo. Severe Air Pollution and Labor Productivity: Evidence from Industrial Towns in China. *American Economic Journal: Applied Economics*, 11(1):173–201, jan 2019.

[2] Sam Heft-Neal, Jennifer Burney, Eran Bendavid, and Marshall Burke. Robust relationship between air quality and infant mortality in Africa. *Nature*, 559(7713):254–258, jul 2018.

[3] The Lancet Neurology. Air pollution and brain health: an emerging issue. *The Lancet Neurology*, 17(2):117, 2018.

[4] Xin Zhang, Xi Chen, and Xiaobo Zhang. The impact of exposure to air pollution on cognitive performance. *Proceedings of the National Academy of Sciences*, 115(37):9193–9197, sep 2018.

Publications and Statement of Contribution

The three core chapters of this thesis (chapters 2 to 4) correspond to the three publications of the cumulative dissertation. They are the result of collaborations in this PhD project between the author of this thesis and his advisors and colleagues. The author of this thesis has made substantial contributions to the contents of all three publications, from conceptual design and technical development to writing.
This section details the contributions of the author to the three publication and acknowledges major contributions from others.

Publication 1 (Chapter 2): ***S. Rauner, J. Hilaire, D. Klein, J. Strefler, G. Luderer, "Air Quality Co-benefits of Ratcheting-up the NDCs," Climatic Change (2020) (accepted). Published under the Creative Commons Attribution 4.0 International license*** *https://creativecommons.org/licenses/by/4.0/. https://doi.org/10.1007/s10584-020-02699-1*

This publication uses the REMIND model which is a continuous development effort of the researcher of the Transformation Pathways group at PIK. The air pollution modeling builds on the work by Jérôme Hilaire. Gunnar Luderer provided guidance and helpful input for the implementation. The author is responsible for the conceptual design of this publication, with input from Gunnar Luderer. The author performed the model runs, analyzed the data, and wrote the publication, with extensive revisions by Gunnar Luderer, the other co-authors and the guest editor Steven Smith.

Publication 2 (Chapter 3): ***S. Rauner & M. Budzinski, "Holistic energy system modeling combining multi-objective optimization and life cycle assessment," Environ. Res. Lett. 12, 124005 (2017) (published). Published under the Creative Commons Attribution 3.0 licence*** *https://creativecommons.org/licenses/by/3.0/. https://doi.org/10.1088/1748-9326/aa914d*

This publication uses the MOROSA model framework which was developed by the author. The life cycle assessment part of the work was developed in cooperation with Maik Budzinski. The author is responsible for the conceptual design of this publication, with input from Maik Budzinski. The author performed the model runs analyzed the data, and wrote the publication in cooperation with Maik Budzinski.

Publication 3 (Chapter 4): ***S. Rauner, N. Bauer, A. Dirnaichner, R. Van Dingenen, C. Mutel, and G. Luderer, "Coal exit health and environmental damage reductions outweigh economic impacts," Nature Climate Change (2020) (accepted).*** *https://doi.org/10.1038/s41558-020-0728-x*

This publication uses the REMIND model which is a continuous development effort of the researcher of the Transformation Pathways group at PIK. The life cycle assessment modeling builds on the work by Alois Dirnaichner, Brian Cox and Chris Mutel. The author is responsible for the conceptual design of this publication, with input from Gunnar Luderer and Nico Bauer. The author performed the model runs, analyzed the data, and wrote the publication, with extensive revisions by Gunnar Luderer, Nico Bauer, Alois Dirnaichner and the other co-authors.

Tools and Resources

All in this dissertation created code and the relevant data is available at `https://github.com/rauner`.

Modeling The REMIND (available at https://github.com/remindmodel/remind) as well as the GESOP model are implemented in GAMS[1]. For REMIND the CONOPT[2] solver was used to solve the non-linear formulations. For GESOP the CEPLEX solver was used to solve the MIP problem.

Data Processing For the data pre- and postprocessing work as well as the plotting of graphs we use R[3].

Typesetting This document was prepared using LaTeX[4].

Literature management Mendeley[5] was used for literature management and providing the bibliography to LaTeX.

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[1] `http://www.gams.com`
[2] `https://www.gams.com/latest/docs/S_CONOPT.html`
[3] https://www.r-project.org/
[4] `http://www.latex-project.org/intro.html`
[5] https://www.mendeley.com/