Challenges for low stabilization of climate change: The complementarity of non-CO_2 greenhouse gas and aerosol abatement to CO_2 emission reductions

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Summary

In the Copenhagen Accord it was recognized that global mean temperature should not exceed 2°C above preindustrial levels. Reaching this target will require deep cuts in CO_2 emissions. However, reducing CO_2 emissions alone will not be enough. To reach stringent climate targets, other substances have to be taken into account as well. In this thesis, I analyze potential bottlenecks for reaching low stabilization targets. My focus is on the complementarity of non-CO_2 greenhouse gas and aerosol abatement to CO_2 emission reductions.

Greenhouse gas emissions rise particularly fast in developing countries. These countries want to sustain their economic growth and reach self-sufficient energy levels, which has historically lead to higher emissions. Without climate policies, currently used integrated assessment models continue this historic pattern. In case of stringent climate policies however, models break with this historical pattern and assume sustained economic growth with very low energy levels. These model results seem to be either not realistic or driven by strong implicit assumptions. In order to determine residual CO_2 emissions we need to either understand or correct these results.

Long-lived non-CO_2 greenhouse gases account for almost one quarter of anthropogenic greenhouse gas emissions. To achieve ambitious climate targets, these gases have to be reduced as well. The Kyoto protocol determined emissions reductions for CO_2, as well as the well-mixed greenhouse gases CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and SF_6. In the Kyoto protocol, emission budgets were determined not for each separate gas, but in one single budget, leaving nations full flexibility as to which greenhouse gas to reduce. This single budget required a metric to make the different gases comparable. In the Kyoto protocol a simple constant metric called the global warming potential was chosen. This metric has been challenged on various grounds and a number of alternatives have been proposed. We analyze different constant and time-dependent metrics with regard to their implications on global economic costs, transient emission pathways, and regional and sectoral impacts. We find that although impacts on global costs are negligible, there are considerable effects on medium term emissions and regional wealth transfers.

In recent model intercomparisons, the possibility to generate negative CO_2 emissions using a combination of bioenergy with carbon capture and storage has proven to be a crucial mitigation option. Low stabilization scenarios become much more costly when bioeenergy is limited or when carbon capture and storage (CCS) is not available. Moreover, bioenergy provides one of the rare alternatives to produce low-carbon liquids fuels. In our study, we analyze bioenergy deployment depending on the stringency of the climate target, the availability of CCS, and bioenergy supply.

Another important group of emissions determining today's radiative forcing are aerosols. They are not controlled under any climate treaty so far, and it seems far more likely that they will rather be subject to air pollution policies than to climate policies. Yet since aerosols contribute substantially to anthropogenic forcing, the question arises how they interact with climate and climate policy. In the literature we find different lines of arguments. Some argue that since overall aerosol forcing is negative, a fast reduction of aerosol emissions could lead to accelerated global warming. Others focus on black carbon, which is an important contributor to warming, and suggest that it should be reduced first as this would lead to synergies between air pollution policies and climate policies. With the model we are using we are able to consider interactions not only between air pollution policies and climate policies, but also between the various aerosol species which are often times co-emitted. We find that air pollution policies are hardly able to influence long-term climate targets. On the other hand, climate policies efficiently reduce air pollutants. Our results suggest that there are synergies rather than trade-offs between air pollution policies and climate policies.

Zusammenfassung

Im Kopenhagen Accord wurde international anerkannt, dass die globale Mitteltemperatur 2 °C über vorindustriellen Werten nicht übersteigen sollte. Um dieses Ziel zu erreichen, sind tiefe Einschnitte in CO_2 Emissionen nötig. Es wird allerdings nicht genügen, nur CO_2 zu reduzieren. Um ansrpuchsvolle Klimaziele zu erreichen müssen auch andere Substanzen berücksichtigt werden. In dieser Arbeit analysiere ich mögliche Schwierigkeiten bei der Erreichung von ambitionierten Klimazielen. Mein Fokus liegt dabei auf der Komplementarität von nicht-CO_2 Treibhausgas- und Aerosolvermeidung zu Reduktionen von CO_2 Emissionen.

Treibhausgasemissionen steigen besonders schnell in Entwicklungsländern. Diese wollen ihr ökonomisches Wachstum erhalten und das dafür nötige Energielevel erreichen, was historisch gesehen zu höheren Emissionen geführt hat. Ohne Klimapolitiken setzen derzeitige integrated assessment Modelle diesen Trend auch fort. Unter Einhaltung stringenter Klimaziele verlassen sie jedoch dieses historische Muster und gehen von kontinuierlichem ökonomischen Wachstum bei niedrigen Energielevels aus. Diese Ergebnisse sind offenbar entweder nicht realistisch oder kommen durch starke implizite Annahmen zustande. Um schwer vermeidbare Sockelemissionen zu bestimmen müssen wir diese Ergebnisse entweder verstehen oder korrigieren.

Langlebige nicht-CO_2 Treibhausgases machen etwa ein Viertel der anthropogenen Treibhausgasemissionen aus. Um ambitionierte Klimaziele zu erreichen müssen diese Emissionen ebenfalls reduziert werden. Im Kyoto-Protokoll wurden Reduktionsziele nicht nur für CO_2 festgelegt, sondern auch für die langlebigen Treibhausgase CH_4, N_2O, SF_6 und Fluorkohlenwasserstoffe. Dabei wurden Budgets nicht für die einzelnen Gase, sondern als Gesamtbudget festgelegt, was den einzelnen Staaten volle Flexibilität bezüglich der zu reduzierenden Gase gibt. Dazu wird eine Metrik benötigt, die die verschiedenen Gase vergleichbar macht. Im Kyoto-Protokoll wurde das sogenannte "global warming potential", eine zeitlich konstante Metrik, gewählt. Diese Metrik wurde seither aus verschiedenen Gründen kritisiert und Alternativen vorgeschlagen. Wir analysieren mehrere konstante und zeitabhängige Metriken im Hinblick auf ihre Implikationen bezüglich globaler ökonomischer Kosten, transienter Emissionspfade, und regionaler und sektoraler Auswirkungen. Obwohl die Auswirkungen auf globale Kosten gering sind, finden wir deutliche Effekte auf mittelfristige Emissionen und regionale Kostentransfers.

Aktuelle Modellvergleichsstudien zeigen, dass die Möglichkeit, durch eine Kombination von Bioenergie und Kohlenstoffabscheidung und -speicherung (CCS) negative CO_2 Emissionen erzeugen zu können, eine entscheidende Vermeidungsoption ist. Ambitionierte Klimaschutzziele werden deutlich teurer, wenn die Verfügbarkeit von Bioenergie begrenzt ist, oder wenn CCS nicht zur Verfügung steht. Darüberhinaus stellt Bioenergie

eine der seltenen Alternativen dar, Kohlenstoffarme Treibstoffe zu produzieren. In unserer Arbeit analysieren wir den Einsatz von Bioenergie in Abhängigkeit von Klimaziel, der Verfügbarkeit von CCS, und der Verfügbarkeit von Bioenergie.
Eine weitere wichtige Gruppe von Emissionen die den heutigen Strahlungsantrieb bestimmen sind Aerosole. Sie werden bisher nicht durch ein Klimaabkommen kontrolliert, und werden wahrscheinlich auch in Zukunft eher Ziel von Luftreinhaltungsabkommen sein. Da Aerosole jedoch substanziell zum menschengemachten Klimawandel beitragen, stellt sich die Frage wie sie mit dem Klima und Klimaabkommen interagieren. In der Literatur gibt es verschiedene Argumentationsstränge. Einige behaupten dass eine schnelle Reduktion von Aerosol Emissionen zu beschleunigter Erderwärmung führen könnte, da sich Aerosole insgesamt kühlend auswirken. Andere konzentrieren sich mehr auf Ruß, der einen wichtigen Bestandteil der derzeitigen Erwärmung ist, und schlagen vor, dass Ruß zuerst reduziert werden sollte, um Synergien zwischen Klimapolitik und Luftreinhaltungspolitik auszunutzen. Mit unserem Modell sind wir in der Lage, nicht nur Interaktionen zwischen Klima- und Luftreinhaltungspolitik zu betrachten, sondern auch Interaktionen zwischen den verschieden Aerosolen, die oftmals gemeinsam ausgestoßen werden. Dabei stellen wir fest, dass Luftreinhaltungspolitiken kaum in der Lage sind, langfristige Klimaziele zu beeinflussen. Dagegen sind Klimaabkommen dazu geeignet, Luftverschmutzung zu reduzieren. Unsere Resultate legen nahe, dass es eher Synergien als Zielkonflikte zwischen Klima- und Luftreinhaltungspolitiken gibt.

Chapter 1

Introduction

1.1 Achieving ambitious climate protection targets

There is widespread international agreement that global warming needs to be limited to prevent dangerous anthropogenic interference with the climate system. In the Copenhagen Accord (UNFCCC, 2009) it was recognized that the global mean temperature should not exceed 2°C above preindustrial levels. This implies tight limits on the long-term anthropogenic forcing (IPCC, 2007). It also implies tight limits on cumulative long-lived greenhouse gases (GHGs)[1] emissions (e.g. Matthews and Caldeira (2008); Meinshausen et al. (2009); Allen et al. (2009)). To reduce emissions, several options are available. As a large share of Kyoto gas emissions arise in the energy sector, these can be reduced by increasing energy efficiency. Abatement of CO_2 and CH_4 emissions can be achieved by substituting fossil fuels with low-carbon technologies such as wind, solar, geothermal, water, or nuclear. CO_2 emissions, e.g. from fossil fuel power plants, can be reduced using carbon capture and storage (CCS). This technology filters CO_2 from exhaust emissions and stores it underground under high pressure. A wide range of mitigation options are available for non-CO_2 Kyoto gases, e.g. better maintenance of gas pipelines to prevent leakage of CH_4, CH_4 recovery from coal mining, changing animal diets to reduce enteric fermentation and nitrogen excretion, improving fertilizer use efficiency, to name just a few (Lucas et al., 2007). Finally, GHG emissions could be compensated for by combining bioenergy with CCS (BECCS). Bioenergy plants absorb CO_2 from the atmosphere in their growing phase. This CO_2 is set free again when the plants are burned to produce energy. Therefore bioenergy generates only N_2O emissions due to fertilizer input and CO_2 emissions related to land conversion and transport, but not to power generation itself. If CCS is used in combination with bioenergy, a large share of the CO_2 the plants absorbed from the atmosphere is not released again, which generates net negative CO_2 emissions.

Fig. 1.1 shows the radiative forcing of the most important forcing agents in 2005. The single most important group consists of the long-lived GHGs CO_2, CH_4, N_2O and fluorinated gases (F-gases), which are also referred to as Kyoto gases, and Halocarbons (also referred to as Montreal gases). Their combined direct forcing in 2011 is about

[1] To compare other long-lived GHGs as CH_4 and N_2O to CO_2, they are converted to CO_2 equivalents (CO_2e) using a metric that considers different physical properties as lifetime and additional radiative forcing caused by an additional unit of the specific gas. The most common metric is the global warming potential.

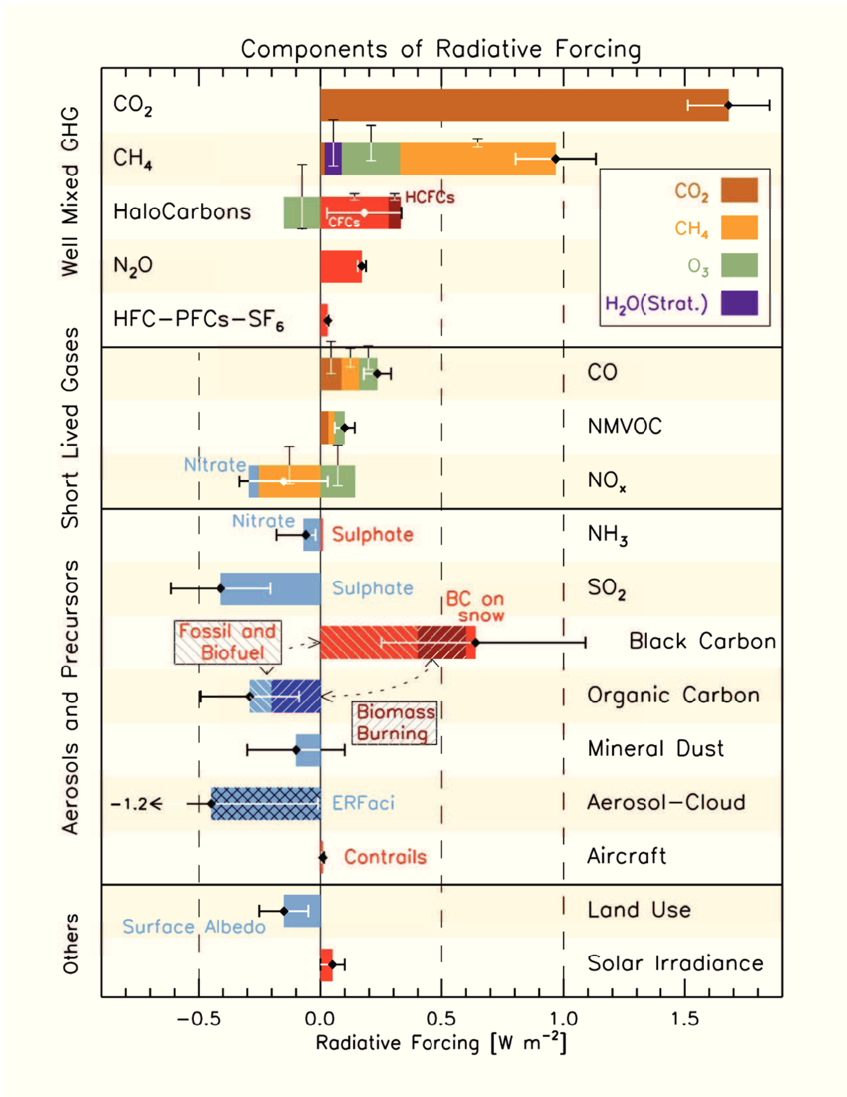
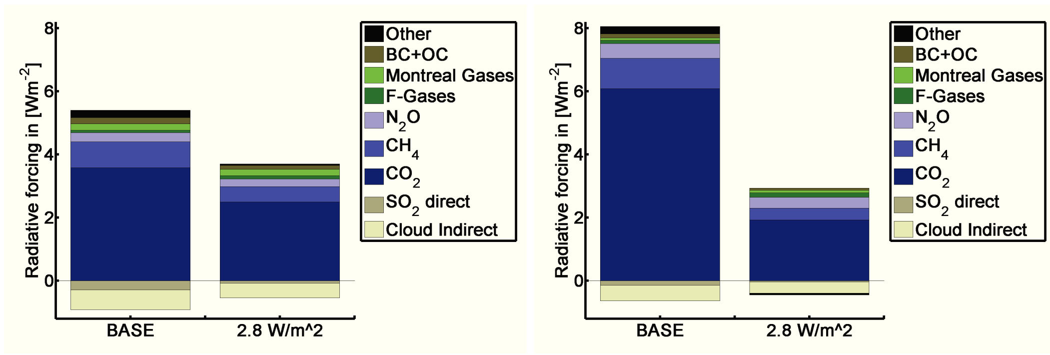


Figure 1.1: Radiative forcing of long- and short-lived substances in 2011. From Myhre et al. (2013).



(a) 2050 (b) 2100

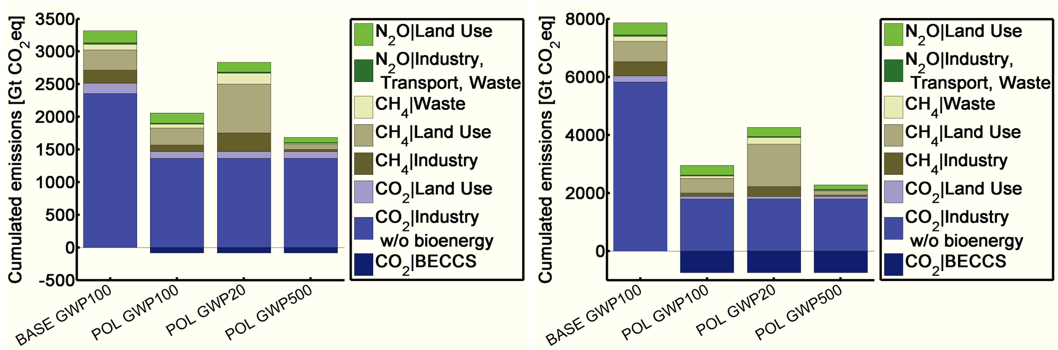
Figure 1.2: Radiative forcing components in a) 2050 and b) 2100 in reference and climate policy case. Data is taken from REMIND results of the EMF27 modeling comparison exercise.

2.83 Wm^{-2}, of which 1.82 Wm^{-2} is contributed by CO_2 alone (Myhre et al., 2013). Short-lived GHGs have only a small direct forcing, but are important for atmospheric processes controlling the concentrations of tropospheric ozone and methane. These indirect effects can be positive or negative and largely cancel out each other in 2011. The third important group are aerosols. Although black carbon leads to positive radiative forcing, the total net effect of aerosols is very likely negative. Aerosol forcing is afflicted with much higher uncertainty than GHG forcing. The central estimate for net aerosol forcing (including albedo changes due to black carbon aerosol deposited on snow) was -1.1 Wm^{-2} in 2005 (Forster et al., 2007) and, with a revised concept called effective radiative forcing which incorporates responses to perturbations, -0.86 Wm^{-2} in 2011 (Myhre et al., 2013). In this thesis, I concentrate on the two groups with the highest radiative forcing contributions, long-lived GHGs and aerosols. Fig. 1.2 shows how the forcing components evolve in a reference case and with a climate target of 2.8 Wm^{-2} in 2100. Long-lived GHGs, especially CO_2 but also CH_4, are the most important contributors to radiative forcing reduction in 2100. Aerosol forcing reductions are more important in the first half of the century. These results were produced using the integrated assessment model REMIND as a part of the EMF 27 study (Kriegler et al., 2013). The model REMIND is an essential tool for this thesis and will be described in more detail in chapters 1.4 and 2.

The single most important gas for anthropogenic climate change is CO_2. CO_2 emissions have to be reduced quickly and substantially in order to limit global warming to 2 °C above pre-industrial levels. Meinshausen et al. (2009) found that around 1200 Gt cumulative CO_2 emissions from 2000-2049 yield a central probability estimate of 67% to stay below 2 °C. According to EDGAR (2011), about 330 Gt CO_2 were already emitted from 2000-2012, with yearly emissions still rising. The most important sources in 2005 were the energy sector (74.6 %), forest and peat fires (19.5 %), and industry process emissions (5.3 %) (EDGAR, 2011). For the energy sector there are many possibilities to reduce emissions, as I already mentioned. However, emissions will still depend on the amount of energy needed. When we look at the final energy per capita demand in developing countries, current integrated assessment models typically assume increasing levels of energy demand with increasing affluence if no climate policy is pursued. This is in line with historic patterns. With increasing stringency of climate policies, however, these historical patterns are violated and developing countries tend to grow economically while their energy demand remains at a very low level. These model results seem to be either not realistic or driven by strong implicit assumptions. In order to determine residual CO_2 emissions, we need to understand these results. A crucial first step would be to determine lower limits for energy demand of specific sectors. One that is rather easily accessible and important for development is cement and steel production for infrastructure. In chapter 3 we use an econometric model to estimate future cement and steel production for infrastructure. This estimate simultaneously yields a lower limit for energy demand for infrastructure and for CO_2 emitted in the cement production process. There is no low-carbon alternative for these emissions, since they arise in a chemical reaction. At most they could be captured and stored. Our results help to determine lower limits for CO_2 residual emissions which are a crucial bottleneck for achieving low stabilization scenarios.

In the representative concentration pathways (RCP) scenarios (van Vuuren et al., 2011) and in many following modeling intercomparison studies, low stabilization scenarios reached around 2.6 Wm^{-2} total radiative forcing in 2100. Even if CO_2 emissions start to decline in 2015 and reach zero in 2060, CO_2 forcing will likely rise to around 1.9 Wm^{-2} in 2100 due to rising emissions today and its long lifetime in the atmosphere. This leaves only 0.7 Wm^{-2} for all other forcing agents combined. In order to achieve such a low stabilization target, non-CO_2 substances have to be reduced as well. Some of the halocarbons are controlled globally under the Montreal protocol. These gases are declining continually on a global level and will therefore quite likely pose no substantial problem. Reducing CH_4 and N_2O makes stringent climate protection targets easier to achieve and substantially reduces costs as it increases the headroom for CO_2 (van Vuuren et al., 2007).

In recent years the necessity of including non-CO_2 Kyoto gases in an emissions budget has not been challenged. However, the method for including these gases is not as definite. If emission budgets are to be used, there could be separate budgets for all gases, or a single budget allowing for trade-offs between the gases (what-flexibility). In the Kyoto protocol the latter approach was chosen. It allows for the market to choose the cheapest abatement option among the different gases, therefore tapping the full efficiency potential. This requires a metric which converts other gases to CO_2 equivalents. So far, the most widely used metric is the 100-year global warming potential (GWP100), calculated as the ratio of the integrated radiative forcing of an additional unit of a given gas over a fixed time horizon to the integrated radiative forcing of the same unit of CO_2. This metric has been challenged on economic and physical grounds (Schmalensee, 1993; O'Neill, 2000; Manne and Richels, 2001; Shine et al., 2005) and alternatives were proposed. The time horizon, for instance, makes a significant difference, yet it is arbitrary. The choice of indicator for climate change is also not at all obvious. Instead of radiative forcing, one could also use temperature, rate of temperature change, or economic damages. Independent of the indicator, metrics can be constant or time-dependent. Emissions of a specific gas are less important for reaching a given climate target when the time until the target gets binding is longer than the lifetime of the gas in the atmosphere. Time-dependent metrics capture this effect and may therefore lead to lower economic costs. A metric that uses global temperature change at a specific point in time in the future instead of integrated radiative forcing is the global temperature change potential (GTP) proposed by Shine et al. (2005, 2007). Given a climate target, integrated

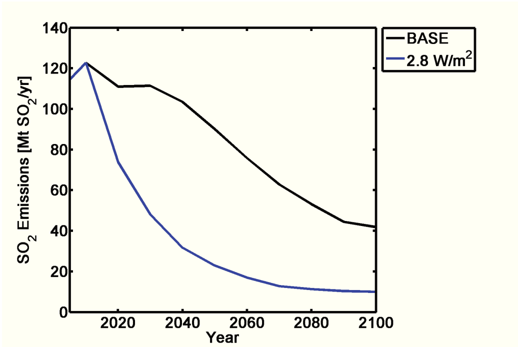


(a) 2050 (b) 2100

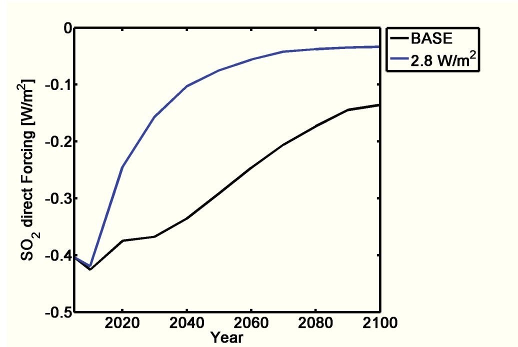
Figure 1.3: Cumulated emissions of Kyoto gases in CO2eq until a) 2050 and b) 2100 in reference and climate policy case. Data is taken from REMIND results of the EMF27 modeling comparison exercise. In the reference case (EMF scenario 1) we used 100-year global warming potentials (GWP100) to convert non-CO_2 emissions to CO_2 equivalents. In the climate policy case (2.8 Wm^{-2} in 2100, EMF scenario 9) we show 100-year, 20-year and 500-year global warming potentials (GWP100, GWP20, GWP500).

energy-economy-climate models can be used to derive cost-optimal emission pathways, with exchange rates of CO_2, CH_4 and N_2O emerging endogenously as the ratios of shadow prices (Manne and Richels, 2001). This ratio of shadow prices is often referred to as global cost potential (GCP, e.g. (Johansson, 2012)). However, an inter-temporal energy-economy climate modeling framework is required to derive GCPs, and their numerical value may depend on many assumptions inherent to the model. By now there are a number of different metrics available, all of which have advantages that make them suitable for specific purposes. Even though they are at least partially derived on a natural science basis, the question of which metric to use cannot be answered by natural sciences alone. The choice of metric implies value judgments on the trade-off of economic costs and timing of emission reductions. The relative importance of the different Kyoto gases under different time horizons is illustrated in figure 1.3. It shows cumulative Kyoto gas emissions until 2050 and until 2100, both with and without climate policy. For the climate policy case, GWPs with three different time horizons of 20, 100, and 500 years are used to convert non-CO_2 gases to CO_2 equivalents. From this graphic we can already see that the choice of metric has a significant influence on the relative importance of the different gases, especially in the medium term. In chapter 4 we investigate the impact of different metrics on the climate and on global and regional costs. Work done in this context has also been picked up in international modeling intercomparison exercises and will be published in the context of the LIMITS project, where at least one publication will be co-authored by the author of this thesis.

Another crucial mitigation option is bioenergy, especially in combination with CCS, which allows for net negative CO_2 emissions. Figure 1.3 shows that by the end of the century, cumulated negative emissions could offset a large fraction of residual emissions from other sectors. Model intercomparison exercises such as EMF27 (Rose et al., 2013a) have documented the option value of this technology. Low stabilization scenarios become much more costly when bioenergy is limited or when CCS is not available (see also chapter 5). Moreover, bioenergy provides one of the rare alternatives to produce low-carbon liquid fuels. This versatility makes bioenergy a very attractive mitigation



(a) SO_2 Emissions



(b) SO_2 direct radiative forcing

Figure 1.4: SO_2 emissions and direct radiative forcing without climate policy (BASE) and under a 2.8 Wm^{-2} radiative forcing target in 2100. Data is taken from REMIND results of the EMF27 modeling comparison exercise.

option. Yet it is one afflicted with a lot of uncertainties. For instance, it is unclear how much bioenergy can be supplied at all. Even if large amounts could be supplied, we need to learn more about the interactions e.g. with food supply or biodiversity. Rising food prices, as well as forest protection, water management, or the need to reduce fertilizer input could make it necessary to employ sustainability bounds on the use of bioenergy. CCS is not yet available, which leads to uncertainties concerning the extent of its availability and its costs. Even if CCS were technologically feasible, social acceptance is by no means granted. For these reasons, it is important to analyze bioenergy deployment and its influence on mitigation costs depending on the stringency of the climate target, the availability of CCS, and the amount of bioenergy supply.
Figure 1.1 shows that aerosols add substantially to current radiative forcing. In contrast to long-lived substances like halocarbons, which are being phased out under the Montreal protocol, aerosols are not controlled under any international environmental agreement. Due to the negative implications of aerosols for human health, air quality, and ecosystems, air pollution policies which aim for the reduction of various aerosol species are already being implemented across the globe. Flue gas desulphurization systems are able to remove more than 90% of SO_2 from flue gas. European law limits SO_2 emissions from new power plants such that flue-gas desulphurization systems have become mandatory. In the U.S., a sulfur emissions trading scheme has helped decrease sulfur emissions by power plants substantially. Emission standards limiting CO, NOx, and particulate matter emissions from motor vehicles have been issued e.g. in the U.S. or in Europe with the Euro-Norm, which is increasingly adopted by other countries as well. Air pollution control measures are likely to be extended, which would lead to continually decreasing aerosol emissions. Since aerosols are co-emitted with CO_2, climate policy would lead to a further decline. Fig. 1.4 shows SO_2 emissions and direct radiative forcing in two REMIND scenarios, a reference case and a climate policy case.

Net aerosol forcing is negative, thus counteracting global warming. Since the lifetime of aerosols in the atmosphere is only in the range of days, this cooling effect is removed very quickly when emissions cease. We can see in Fig. 1.4 that radiative forcing reacts immediately to the change in emissions. Therefore some have warned that global warming could be accelerated if aerosol emissions were reduced too quickly. In chapter

6 we analyze how aerosol forcing evolves with and without climate policy. In addition, we analyze the impact of different air pollution policies on medium- and long-term climate targets. This enables us to analyze synergies and trade-offs between air pollution and climate policies. Work done in the context of this thesis was incorporated in the international modeling exercise EMF27 and was published as Rose et al. (2013b).

1.2 Atmospheric physics

1.2.1 The bare rock model

A very simple reasoning for the existence of the natural greenhouse effect is to look at the mean temperature of the Earth without the atmosphere. Following Archer (2007), we calculate this mean temperature using the bare rock model, i.e. treating the Earth as a homogeneous sphere with a homogeneous mean temperature. In this model, the mean temperature of the Earth is determined only by its radiative balance. The equilibrium temperature is reached when the energy input by the Sun equals the energy output. The energy input remains constant and can be calculated as the fraction of energy flux from the Sun absorbed by the surface of the Earth

$$F_{in} = \pi R^2 * (1-\alpha) I_{in}, \tag{1.1}$$

where F_{in} denotes the incoming energy flux, R the radius of the Earth, α Earth's albedo, and I_{in} the intensity of incoming sunlight. Present-day earthly albedo is around $\alpha = 0.33$ (Archer). The energy intensity coming from the Sun has recently been measured to be I_{in} = 1360.8 Wm^{-2} at the average distance from Sun to Earth (Kopp and Lean, 2011; Myhre et al., 2013). The energy radiating off the Earth's surface can in first order be described as black body radiation, which depends on the surface temperature T as

$$I_{out} = \varepsilon\sigma * T^4. \tag{1.2}$$

σ denotes the Stefan-Boltzmann constant and is equal to $5.67 * 10^{-8} \frac{W}{m^2 K^4}$. ε is the emissivity, which equals one for a perfect blackbody. The total energy flux can be calculated as the energy intensity times the area it radiates off, i.e.

$$F_{out} = 4\pi R^2 * \sigma * T^4, \tag{1.3}$$

here assuming $\varepsilon = 1$. Balancing incoming and outgoing energy flux $F_{in} = F_{out}$, we can calculate Earth's mean temperature to $T = \sqrt[4]{\frac{(1-\alpha)I_{in}}{4\sigma}} = 251.8K$. This corresponds to the apparent temperature of the Earth as seen from space. Yet, Earth's mean surface temperature is around 288K. This difference can be explained with the natural greenhouse effect.

1.2.2 The natural and anthropogenic greenhouse effect

The greenhouse effect is caused by the concentration of CO_2 and other infrared-absorbing gases in the atmosphere. In the bare rock model Earth and Sun were treated as black bodies. They are not perfect blackbodies, but the approximation works quite well. When looking at their blackbody spectra, one can see that due to its higher temperature, most of the light emitted by the Sun is in the range of about 0.2 - 4 μm with a peak wavelength of about 0.5 μm, whereas Earth radiates between 4 and 50 μm with a peak wavelength of about 10 μm. Greenhouse gases have their absorption bands in the infrared spectrum of the Earth. Therefore sunlight is hardly affected by greenhouse gases, but a fraction of the infrared radiation emitted by the Earth is absorbed. The absorbed energy is again emitted in all directions, thus being partly emitted back toward the Earth. This decreases Earth's outgoing energy flux, which leads to a higher equilibrium surface temperature.

The largest contributor to the natural greenhouse effect is water vapor. However, natural evaporation by far exceeds anthropogenic emissions. Therefore tropospheric water vapor is not considered to be an anthropogenic greenhouse gas (Myhre et al., 2013). In the stratosphere, increased anthropogenic CH_4 emissions lead to an additional source of water vapor. This stratospheric water vapor is considered a contributor to anthropogenic climate change, though its contribution is much smaller than that of CO_2 or CH_4 (Myhre et al., 2013). In contrast to CO_2, water vapor can condense and precipitate, with its amount in the atmosphere being controlled mostly by air temperature. With rising air temperature the maximum amount of water vapor in the atmosphere increases, which amplifies the greenhouse effect. This process is not interpreted as a radiative forcing, but rather as a feedback effect (Myhre et al., 2013).

Naturally, CO_2 is already abundant in the Earth's atmosphere. In preindustrial times, CO_2 concentration was about 278 ppm. Due to anthropogenic emissions, CO_2 concentration has risen to about 390.5 ppm in 2011 (Myhre et al., 2013). The radiative forcing associated with rising CO_2 concentration can be calculated as

$$\Delta F = 5.35 * ln\left(\frac{C}{C_0}\right), \tag{1.4}$$

where ΔF denotes the change in radiative forcing, C the CO_2 concentration in ppm, and C_0 the unperturbed CO_2 concentration in ppm (Ramaswamy et al., 2001).

CH_4 and N_2O also absorb light in an infrared range and therefore add to the greenhouse effect. As they are naturally not as abundant as CO_2, additional emissions have a much higher effect. This is partly compensated by the position of their absorption bands, which are not as central as the absorption bands of CO_2 and therefore cover a smaller amount of energy. Their greater warming effect is reflected in their much higher global warming potentials.

Long-lived GHGs like CO_2, CH_4, and N_2O differ not only in their warming potentials, but also in their atmospheric lifetimes. Particularly CH_4 has a much shorter lifetime in the atmosphere than CO_2 and N_2O. This makes different gases hard to compare as it implies a trade-off between faster short-term warming and higher long-term warming. The implications of this trade-off are discussed in chapter 4.

1.2.3 The carbon cycle

The atmosphere today contains about 828 GtC (Ciais et al., 2013). It exchanges carbon with the terrestrial biosphere, the ocean, and, on very long timescales, the lithosphere. The terrestrial biosphere takes up carbon when plants grow, and releases it when plants and animals respire or dead plants decay. Since growth occurs in spring and summer, and decay in fall and winter, there are seasonal cycles in the carbon flux. The terrestrial biosphere contains about 450 to 650 GtC living carbon and 1500 to 2400 GtC dead carbon in litter and soils. The flux between the terrestrial biosphere and the atmosphere is about 123 GtC per year. The ocean contains about 700 GtC of dissolved organic carbon. The pool of dissolved inorganic carbon is much larger, around 38,000 GtC (Ciais et al., 2013).

The flux between ocean and atmosphere is about 90 GtC per year (Archer, 2007). The weathering of rocks occurs on much larger timescales, leading to relatively small carbon flux of less then 0.1 GtC per year.
The carbon cycle explains the connection between carbon emissions and CO_2 concentration in the atmosphere. To understand the cycle, a number of interactions and feedbacks have to be taken into account. Higher carbon emissions alter the fluxes between the atmosphere, biosphere and ocean. These processes happen on different timescales. Interaction with the biosphere, soils and the upper ocean usually takes place in the range of years to centuries. Deeper soils and the deep sea exchange carbon within centuries to millennia, and interactions with geological reservoirs such as deep-sea carbonate sediments may take up to millions of years (Ciais et al., 2013).
A higher CO_2 concentration leads to faster growth of plants and therefore more carbon uptake by the biosphere. Due to the lack of experiments outside of temperate climates and uncertainties concerning the limitations of this CO_2 fertilization effect due to nutrient limitations, the magnitude of this effect is afflicted with significant uncertainties (Ciais et al., 2013). The flux between the ocean and the atmosphere depends on the partial CO_2 pressure in both and on the temperature of the ocean. Warmer water has a lower ability to take up CO_2. If CO_2 emissions were significantly reduced, and in addition CCS in combination with bioenergy (BECCS) were deployed extensively, this might decrease CO_2 concentration in the atmosphere, thus reducing the partial CO_2 pressure. This could lead to enhanced outgassing of CO_2 out of the oceans, which would cancel some of the effect of BECCS.
The lifetime of CH_4 in the atmosphere is determined by three main sinks: bacterial uptake in soil, stratospheric loss, and tropospheric reaction with hydroxyl,

$$OH + CH_4 \rightarrow CH_3 + H_2O, \tag{1.5}$$

which is the dominant process. “The chemical coupling between OH and CH_4 leads to a significant amplification of an emission impact; i.e., increasing CH_4 emissions decreases tropospheric OH which in turn increases the CH_4 lifetime and therefore its burden" (Myhre et al., 2013).
The main sink for atmospheric N_2O is through photolysis and oxidation reactions in the stratosphere. Currently, the lifetime of N_2O is estimated to be around 131 years. However, N_2O emissions affect stratospheric NO_y concentration and lead to ozone depletion, which leads to a feedback effect on its own lifetime (Myhre et al., 2013).

1.2.4 Carbon climate response

Long-lived GHGs mix well in the atmosphere. Therefore we can assume that their concentration is relatively homogeneous across the globe. Increasing greenhouse gas concentrations lead to higher absorption of the Earth’s infrared emission, thereby altering the energy balance of the Earth. The effect on the energy balance is measured in radiative forcing (RF). In the fifth assessment report of the IPCC, radiative forcing is defined as “the net change in the energy balance of the Earth system due to some imposed perturbation" (Myhre et al., 2013). Radiative forcing is usually expressed in watts per square meter. If radiative forcing changes, the equilibrium temperature of the Earth changes as well. In the fifth assessment report of the IPCC, the relationship between a sustained change in radiative forcing and the equilibrium global mean temperature is given as

$$\Delta T = \lambda RF, \tag{1.6}$$

where λ is the climate sensitivity parameter (Myhre et al., 2013). The equilibrium climate sensitivity, defined as “the warming in response to a sustained doubling of carbon dioxide in the atmosphere relative to pre-industrial levels" (Hartmann et al., 2013), is between 1.5 °C and 4.5 °C, with a most likely value between 2 °C and 3 °C. It is a major source of uncertainty in the climate system. As all these climate variables are closely interrelated, limits on one imply limits on others, too. Limiting global warming to 2 °C above preindustrial temperature therefore implies tight limits on total radiative forcing as well.

The most common way to assess climate impacts of emissions is to calculate atmospheric concentrations and, from these, radiative forcings. Matthews et al. (2009) found an alternative and rather intuitive way to assess the global temperature response to CO_2 emissions, which they called “carbon-climate response". It is defined as the global mean temperature change over a certain time period divided by the global cumulative CO_2 emissions in the same period. By expressing a direct relation between emissions and temperature response, it combines the carbon cycle, climate response to changes in atmospheric concentrations, and climate-carbon feedback. This relationship happens to be almost constant over time, mainly because two effects cancel each other: The fraction of CO_2 remaining in the atmosphere decreases over time as CO_2 is taken up by various sinks. The temperature response, on the other hand, increases over time due to the inertia of the climate system. After an initial adjustment period of about one decade, the temperature response remained at about 1.7 °C per Tt C. Collins et al. (2013) assessed this transient climate response to cumulative carbon emissions (TCRE) to be likely between 0.8 °C and 2.5 °C per Tt C, for cumulative emissions less than about 2 Tt C.

1.2.5 Aerosols

Aerosols originate from emissions of primary particulate matter or formation of secondary particulate matter from gaseous precursors. Main aerosol species are sulfate, nitrate, ammonium, sea salt, mineral dust, organic carbon (OC) and black carbon (BC). BC and partially also OC arise from incomplete combustion of fossil and biomass based fuels. The exact emission factors depend mainly on combustion temperature and oxygen mixtures (Boucher et al., 2013). Aerosol lifetimes in the troposphere are usually in the range of days to weeks.

In contrast to greenhouse gases, aerosols are not transparent for the radiative spectrum emitted from the Sun. Sulfate aerosols and organic carbon scatter sunlight and reflect part of it back to space, resulting in a negative radiative forcing contribution. Black carbon, on the other hand, absorbs visible light coming from the Sun, leading to a positive radiative forcing contribution. In particular black carbon aerosols on snow reduce land albedo, which is usually accounted for as a separate effect of black carbon.

In addition to these direct effects of aerosols absorbing or reflecting sunlight, there are indirect effects, which mainly relate to the interaction of aerosols and clouds. Aerosols serve as condensation nuclei for water vapor. An increased concentration of aerosols leads to a larger number of smaller droplets, which alters cloud properties in two ways. First, it increases cloud albedo (Twomey, 1977), and second, it increases the lifetime of clouds (Albrecht, 1989). Both effects cool the atmosphere.

There are further effects which make aerosol cloud interaction more complicated. These include feedback effects of clouds on aerosols, the dependence of aerosol indirect effects on particle size and mixing state and interactions between aerosols and ice clouds (Boucher et al., 2013). The complexity of aerosol cloud interaction has been the subject of research in the last years, but is still not fully understood, thus leading to high uncertainty regarding especially aerosol indirect forcing, which dominates the uncertainty of anthropogenic radiative forcing.

1.3 Integrated assessment modeling

Our overarching research question is how to achieve low stabilization targets at minimal economic costs. Since the largest share of climate relevant emissions arises from the energy system, we need to describe possible transformation pathways of the energy system, which then provide a range of action alternatives for policy makers. To find cost efficient pathways, we cannot describe the energy system independently, but need to consider interactions with the economy, climate, agriculture, industry, etc. A detailed description of all these variables requires a comprehensive model which is able to provide plausible scenarios of how the future might evolve, integrating different sectors and considering technological and socio-economic changes.
Scenarios explore a large space of possible futures under given circumstances and assumptions. They depend heavily on assumptions, e.g. availability and costs of CCS, learning curves in renewable technologies, or food demand depending on population development. To provide robust policy options, integrated assessment models aim to provide a broad range of possible future developments and their implications, while transparently showing their assumptions and requirements. Efforts like the development of shared socio-economic pathways (SSPs) aim to cover a broad scenario space (Ebi et al., 2013; O'Neill et al., 2013). This enables policy makers to assess uncertainties connected to parameters like population growth, but also to technological parameters like renewable or fossil fuel availability and social and behavioural parameters like dietary preferences, environmental awareness or international cooperation.
By now a wide range of different integrated assessment models are available. They differ in their level of detail, structure, solution method, and time horizon. In the following we will discuss some alternative model structures and their implications for suitable research questions and scenario outcomes.
Level of detail: Models are often broadly distinguished into bottom-up and top-down models. However, Fischedick et al. (2011) noted that these terms are used differently in different contexts. In general, bottom-up models describe the energy sector in great detail, but lack macroeconomic detail. Top-down models represent all sectors, which comes at the cost of sectoral detail. A comparison between results of both model groups can be found in Barker et al. (2011). To answer the questions we raised, we need to describe interactions between resource extraction; energy use in industrial, residential and commercial, and transport sectors; emissions from all sources; and the climate. Therefore we use a hybrid model, which combines the sectoral coverage of a top-down model with a high level of detail in the energy sector.
Formation of expectation: Recursive dynamic models like GCAM calculate each time step based on past information and imprecise expectations about the future. Intertemporal optimization models, on the other hand, have perfect foresight. At each point in time they have perfect knowledge about future events and they expect perfect future markets. This makes them suitable to address issues like endogenous depletion of fossil resources or banking and borrowing of GHG allowances. They are expected to allocate emissions more efficiently over time, which would lead to lower global costs. In our studies, we investigate the deployment of bioenergy, especially in combination with CCS which generates negative emissions. Perfect foresight allows us to anticipate future bioenergy demand and the implications of future negative emissions, which affects the timing of bioenergy deployment. In another study, we analyze the impact of different emission metrics. To

evaluate these impacts, we need an intertemporal optimal emission path as a benchmark.
Solution method: Models may also differ in the way climate targets are implemented. They could either require a pre-defined target to be met at minimal costs (cost-effectiveness) or internalize climate damages and calculate the overall economic optimum (cost-benefit, e.g. FUND (Anthoff and Tol, 2013)). Cost-effectiveness analysis can be interpreted as a special case of cost-benefit analysis, where damages are zero before the target and infinite afterwards. The advantage of this method is, that no evaluation of damages is required. As of today, climate damages are very uncertain. Models usually use a simple function of global mean temperature, e.g. a quadratic polynomial. In this framework, the exact choice of damage function determines optimal temperature outcomes. For our research questions, we do not need to incorporate damages into the model and thereby avoid the major uncertainty of damage functions by using a cost-effectiveness analysis. In a cost-effectiveness mode the climate target is defined explicitly, which enables the model to calculate cost-optimal solutions for various stringencies of climate policies.
Time horizon: The time horizon is somewhat arbitrary, but needs to fulfill some requirements. It has to be long enough to capture the transformation process of the energy system as well as the relevant time scales for reaching climate stabilization. The first process takes several decades. Current policies already specify goals like 80% CO_2 emission reduction by 2050 in Germany. In the Copenhagen Accord (UNFCCC, 2009), a large number of countries agreed to constrain global temperature change to two degrees above preindustrial levels. Current models usually do not cross this threshold before the middle of the century. For these reasons, the time horizon cannot be less than 2050. Ambitious climate protection targets require total radiative forcing to peak and decline. Since forcing peaks tend to be reached around the middle of the century, we chose 2100 as the relevant time horizon to also capture the decline.

1.4 Methodological approach

For our analysis, we use the multi-regional integrated assessment model REMIND (Bauer et al. (2012); Leimbach et al. (2010); Luderer et al. (2013)). Each single region is modeled as a hybrid energy-economy system and is able to interact with the other regions by means of trade. Tradable goods are the exhaustible primary energy carriers coal, oil, gas and uranium, a composite good, and emission permits.
The economy sector is modeled as a Ramsey-type growth model which maximizes utility, a function of consumption. Labor, capital and end-use energy generate the macroeconomic output, i.e. GDP. The produced GDP covers the costs of the energy system, macroeconomic investments, the export of a composite good and consumption.
The energy sector is described with high technological detail. It uses exhaustible and renewable primary energy carriers and converts them to final energies such as electricity, heat and fuels. Various conversion technologies are available, including technologies with CCS. A detailed documentation of the REMIND model is provided by Luderer et al. (2013).
REMIND accounts for various emissions types and sources. Long-lived GHGs (CO_2, CH_4, N_2O, F-gases, Montreal gases), short-lived GHGs (CO, NO_x, VOC), and aerosols (SO_2, black carbon, organic carbon) are represented with different levels of detail. In the energy system, CO_2, SO_2, black carbon (BC) and organic carbon (OC) emissions are calculated on a technology level. The energy system provides information on regional consumptions of fossil fuels and biomass by region, time step and technology. For each fuel, region, and technology, an emission factor for the specific gas is applied to calculate the emissions. CH_4 emissions arise from extraction and distribution of fossil fuels and therefore depend on the amount of extracted fossil fuels in each region. CO_2 emissions from cement production and N_2O and CH_4 emissions from waste handling are estimated as a function of economic drivers using an econometric model. Other emission sources such as agriculture, industrial processes, or forest and savanna burning are added exogenously. CO_2 from land-use change, N_2O, and CH_4 have mitigation options independent from energy consumption or other drivers. The mitigation options are described by marginal abatement cost curves, which provide the percentage of avoided emissions as a function of costs up to a certain maximum. A detailed description of the different types of emissions and their sources and implementation is given in the technical documentation in chapter 2.
Without a hard-coupled climate module, we would only be able to employ climate targets via an emission budget or a carbon tax. With a climate module, we are able to constrain climate variables like total radiative forcing or temperature directly. There is a fundamental difference between these types of targets. If emissions are to be constrained directly via a budget or a tax, the question arises how to include non-CO_2 gases. One could choose a separate budget or tax level, respectively, but the question of how to determine that budget or tax would remain. The most common method is to convert non-CO_2 emissions to CO_2 equivalents. This requires a conversion metric. If emissions are constrained indirectly, via a forcing or temperature target, prices of non-CO_2 gases emerge endogenously as shadow prices. The ratio of their shadow price to the shadow price of CO_2 can be interpreted as a model-internal metric, which is also called global cost potential (GCP). In chapter 4 we compare these types of climate targets and their implications for global and regional economic costs and emission outcomes.

We use a two-tiered approach to couple the energy-economy model to a climate module. A reduced-form climate model is hard coupled to the energy-economy model. It calculates concentrations and radiative forcing of the long-lived GHGs CO_2, CH_4, and N_2O, and radiative forcing of the aerosols SO_2, BC, and OC from the respective emissions. The carbon cycle is modeled via an impulse-response function (IRF) with three timescales reflecting the different timescales of the biosphere, a mixed ocean layer and the deep ocean, based on the Bern carbon cycle model (Joos et al., 1996). The concentrations of CH_4 and N_2O are calculated by single-reservoir box models (Tanaka and Kriegler, 2007). Radiative forcing of long-lived GHGs is calculated based on the equations in the IPCC third assessment report (Ramaswamy et al. (2001), Table 6.2). Direct radiative forcing by sulfate aerosols and indirect aerosol effects are calculated based on Joos et al. (2001). Direct radiative forcing of BC and OC is calculated by simple linear forcing-abundance relationships (Meinshausen et al., 2011). Radiative forcing of other relevant forcing agents (F-gases, Montreal gases, nitrates, mineral dust, stratospheric and tropospheric ozone, stratospheric water vapor, albedo change, carbonaceous aerosols from biomass burning) are added exogenously from RCP6 (Fujino et al., 2006), RCP45 (Smith and Wigley, 2006), and RCP3PD (van Vuuren et al., 2007), respectively, depending on the climate target. According to (Hooss et al., 2001), IRF models are an efficient method to reproduce output from a sophisticated climate model. Therefore we use an impulse-response function based on Hooss et al. (2001) with two timescales to calculate global mean temperature change as a function of total radiative forcing. The IRF was related to a 2-box (surface and deep ocean) energy balance climate model using the same approach as presented in Hooss et al. (2001) for the carbon cycle. Establishing the equivalence between an IRF and energy balance models enabled us to describe the impact of different assumptions about climate sensitivity on the IRF model. The more complex climate model MAGICC6 Meinshausen et al. (2011) can be coupled to REMIND in a post-processing mode.

In scenarios with a forcing target, the target is set on Kyoto forcing only, which is adapted iteratively so that the total forcing target is met. This is to exclude non-Kyoto substances, especially SO_2, from the optimization routine. SO_2 emissions lead to negative forcing, which would lead to a negative shadow price if it were included in the climate target. The model would have an incentive to emit as much SO_2 as possible to make use of its negative forcing. Since sulfate aerosols have negative impacts on human health and ecosystems, high SO_2 emissions are not intended by climate policies. In the context of geo-engineering it is sometimes discussed whether sulfur could be used to mitigate global warming. However, in this case it would be injected in the stratosphere, where its lifetime in the atmosphere would be about 1-2 years, compared to weeks in the troposphere, and its effects on air quality would be lower (Crutzen, 2006). To prevent high SO_2 emissions when the target is on temperature, we fix SO_2 emissions within the optimization routine and update the emission trajectory after each iteration. This problem is much less pronounced for organic carbon. Though its forcing is negative as well, it is co-emitted with black carbon, whose positive forcing cancels the climatic benefits.

1.5 Thesis objective and outline

The aim of this thesis is to analyze how reductions in non-CO_2 long-lived GHGs and aerosols complement CO_2 emission reductions in the achievement of low stabilization scenarios. Thereby I focus on mitigation options that are complementary to the reduction of CO_2 from fossil fuel burning. I identified two groups of emissions important for being able to achieve low stabilization scenarios at justifiable economic costs: The ability to reduce non-CO_2 Kyoto gases and the possibility of generating negative CO_2 emissions using BECCS. Concerning a third group, aerosols, present literature is ambiguous. In general, aerosols lead to global cooling and are therefore often thought to counteract CO_2, especially as they are co-emitted in the burning of fossil fuels. Since they contribute a substantial part of 2005 radiative forcing, these substances form the third group of emissions I analyze.
I approached these research questions using the model REMIND. To be able to use this model for answering my research questions, I first had to implement and refine non-CO_2 emissions and abatement options. The details of my methodological approach are documented in chapter Two. Chapter Three is concerned with possibly rising CO_2 emissions in developing countries. Chapter Four investigates the impact of non-CO_2 Kyoto gas emissions. Chapter Five analyzes the importance of negative CO_2 emissions using the combination of CCS with bioenergy. In chapter Six we study the impact of aerosol emissions and their possible abatement on global climate and climate policy. The focus of this work lies on chapters Four and Six. Chapter Seven presents a synthesis and discussion of results and outlook on further research. Here I present the research questions addressed in each chapter together with a short overview of results.

Technical documentation (Chapter 2)
In this chapter I document in detail my methodological approach. I explain the most important sources of all relevant emissions and how they are implemented. I show how emission factors and other parameters necessary for the implementation are derived. I also present abatement options and their implementation.

Do current integrated assessment models underestimate the energy demand in developing countries? (Chapter 3)
In current integrated assessment models, an ambitious climate policy often leads to very low levels of final energy per capita in developing regions. When comparing current human development indices (HDI) with energy availability, we see that countries below 40 GJ per capita are rarely found to have high or very high development levels. On the other hand, almost all regions with high or very high development levels consume more than 40 GJ per capita. The literature does not provide sufficient reasoning for this threshold. Therefore we estimated the energy demand for infrastructure, which explained about half of this level. Our results suggest that self-sufficient energy demand leads to emissions which may have been underestimated so far.

How does the choice of greenhouse gas emissions metric affect transformation pathways? (Chapter 4)
Multi-gas mitigation strategies require exchange ratios, so called greenhouse gas emission metrics, to include non-CO_2 GHGs into the accounting and evaluation of emissions. The Kyoto protocol used 100-year global warming potentials (GWP). It is a simple and fixed metric; however, it has its shortcomings. Physicists and economists criticized the GWP on various grounds, and a number of alternative metrics have been proposed. We investigate the influence of the choice of metric on global and regional economic costs and on medium term climate indicators. We find that the choice of metric has little influence on global costs, but leads to regional distributional effects. These regional effects are most pronounced when global emission permit trading is taken into account. In terms of climate outcomes, we find that there is little room for effectiveness increases. Overall, the 100-year GWP performs well despite its simplicity.

How do bioenergy deployment and revenues depend on the availability of CCS, stringency of climate target, and bioenergy supply? (Chapter 5)
Bioenergy is a particularly valuable mitigation option for two reasons: first, bioenergy can be converted to liquids to substitute oil, which is mainly used in the transportation sector. This sector has proven to be harder to decarbonize than the heat and power sector, where low-carbon technologies such as wind and solar power are already available. Secondly, the possibility to generate negative CO_2 emissions using BECCS has proven to have the largest influence on global costs for stringent climate policies. We find that bioenergy is predominantly used to produce liquid fuels. If CCS is available, bioenergy is exclusively used in technologies with CCS, and if the carbon price is high enough, the negative carbon content creates more revenue than the energy content.

Can air pollution policies accelerate global warming? (Chapter 6)
Recent publications (Ramanathan and Feng, 2008; Kopp and Mauzerall, 2010) have suggested that a fast reduction of aerosol emissions, especially SO_2, could accelerate global warming and make ambitious climate protection targets harder to reach or even unachievable. In our study we investigate the impact of aerosol emissions on short- and long-term climate. Specifically, we employ different stringencies of air pollution policies and compare their impact on climate targets. We find that air pollution policies have almost no impact on medium- and long-term climate targets. A significant effect on long-term temperature development can only be reached at emissions levels exceeding today's levels by more than 100%, which is very unlikely to occur due to adverse health effects. The rate of temperature change can be affected in the first decades, afterwards climate policy is more important. The effect of this short-term rate of temperature change on ecosystems is uncertain, making further research in this area desirable.

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Chapter 2

Non-CO_2 Emissions in REMIND. A Technical Documentation.

J. Strefler

1 Non-CO_2 Kyoto gases

The substances covered in the Kyoto protocol are often referred to as Kyoto gases. These are CO_2, CH_4, N_2O and fluorinated gases (F-gases). F-gases comprise a number of compounds, which can be classified as Hydrofluorocarbons (HFCs), perfluorated compounds (PFCs) and SF_6. They are characterized by very high global warming potentials (GWPs) and especially in case of PFCs very long lifetimes in the range of around 1000 up to 50'000 years Myhre et al. (2013). The GWP is a widely used metric to compare different greenhouse gases. It is defined as the integrated radiative forcing induced by an additional unit of a specific gas over a predefined time horizon, normalized to CO_2. Figure 1 shows the composition of Kyoto gases with non-CO_2 gases converted to CO_2eq using 100 year GWP.

According to EDGAR (2011), the most important anthropogenic CH_4 sources are agriculture, fugitive emissions from fossil fuel extraction and processing, waste disposal and handling, open burning, and residential energy use. For N_2O the most important sources are agriculture, industrial processes, open burning, energy system, waste disposal and handling, and transportation. These sources are captured in the REMIND model. Emissions from the energy system are endogenous. They are calculated by source, using constant, fuel-specific emission factors. Emissions from agriculture are taken from the model of agricultural production and its impact on the environment (MAgPIE) (Lotze-Campen et al., 2008). N_2O emissions Bodirsky et al. (2012) directly related to bioenergy deployment are accounted for via an additional emission factor on purpose-grown bioenergy, which was also derived from MAgPIE. Emissions from open burning and fossil fuel burning are assumed to remain constant at 2005 levels as reported in EDGAR (2011). N_2O emissions from transportation and industry are exogenous. This is summarized in Table 1. F-gases are exogenous and taken from the RCP6 (Fujino et al., 2006), RCP45 (Smith and Wigley, 2006), and RCP3PD (van Vuuren et al., 2007), respectively, depending on the climate target.

In the following we explain how endogenous emission factors are derived. All types of emissions except open burning have abatement options implemented via marginal abatement cost (MAC) curves on a regional level. The regional disaggregation used in the REMIND model is shown in Table 2. In our model, abatement potentials are based on Lucas et al. (2007), which are time- and source dependent.

1.1 CH_4 from fossil fuel extraction

CH_4 emissions in the energy system arise mainly from coal extraction, gas production, processing and transportation, and oil production. We therefore couple the emissions to the amount of fuel extracted and assign it to the region which extracts the fuel, not the region which consumes it. The emission factors have the unit $[TgCH_4/TWa]$. They are calculated by dividing the emissions in 2005 caused by a specific fuel in a specific region Emi^{regi}_{fuel} by the amount of fuel F^{regi}_{type} extracted in that region. Data for fuel extraction in 2005 is taken from REMIND, which originally is based on data from the international energy agency (IEA). Emission data is taken from the emission inventory EDGAR (2011). EDGAR reports fugitive emissions in the two categories "fugitive emissions from solid fuels" and "fugitive emissions from

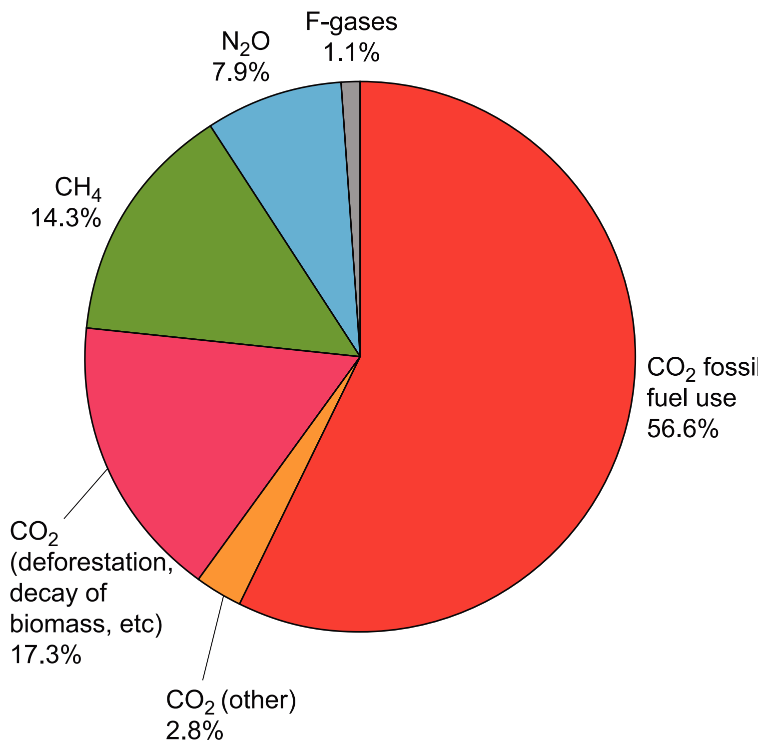

Figure 1.1b *Global anthropogenic greenhouse gas emissions in 2004.*
Source: Adapted from Olivier et al., 2005, 2006

Figure 1: Kyoto gases in CO_2eq from AR4, WG3, CH1, Fig. 1b

Table 1: Sources and implementation of CH_4 and N_2O emissions.

Gas	Sector	% of total	Implementation	Source
CH_4	Agriculture	41.6	Exogenous	MAgPIE
	Fugitive emissions from fossil fuels extraction and processing	31.3	Endogenous	Region- and technology-specific emission factors (Chapter 1.1)
	Waste disposal and handling	16.8	Endogenous	Econometric estimate (Chapter 1.2)
	Open burning	6.4	Exogenous	Constant at 2005 levels
	Residential energy use	3.4	Endogenous	Emission factors for solids from coal and biomass
	Other	0.5	Neglected	
N_2O	Agriculture	54.4	Exogenous	MAgPIE
	Industrial processes	13.5	Exogenous	van Vuuren
	Open burning	12.7	Exogenous	Constant at 2005 levels (EDGAR, 2011)
	Fossil fuel burning	7.1	Exogenouse	Constant at 2005 levels (EDGAR, 2011)
	Energy system	5.6	Endogenous	Fuel-specific emission factors
	Waste	3.5	Endogenous	Econometric estimate (Chapter 1.2)
	Transportation	2.8	Exogenous	van Vuuren
	Other	0.5	Neglected	

Table 2: World regions in REMIND.

Model region	Countries
AFR	Sub-Saharan Africa w/o South Africa
CHN	China
EUR	EU27 countries
IND	India
JPN	Japan
LAM	All American countries but Canada and the US
MEA	North Africa, Middle Eastern and Arab Gulf Countries, Resource exporting countries of FSU, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states, Turkey, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

Table 3: CH_4 emissions in 2005 from fossil fuel extraction in [Tg] and emission factors in [$TgCH_4$/TWa] for coal, oil, and gas.

	CH_4 emissions in 2005			Emission factors		
Region	EDGAR	NIR	REMIND	Coal	Oil	Gas
USA	9.61	9.39	9.79	5.17	2.57	7.70
JPN	0.10	0.03	0.11	5.17	2.37	5.24
EUR	6.76	1.74	7.28	10.76	1.41	12.97
RUS	17.73	16.95	17.73	15.17	2.70	20.78
MEA	19.14	-	19.13	19.28	1.43	23.03
CHN	25.27	-	25.27	14.87	1.50	31.09
IND	2.52	-	2.54	7.76	2.32	18.17
AFR	4.59	-	1.19	19.28	1.43	23.03
LAM	7.10	-	7.10	21.10	1.19	24.98
OAS	6.71	-	6.71	14.64	3.26	13.65
ROW	8.76	-	8.76	6.11	3.48	9.72
Total	108.28	-	105.62			

oil and gas". There is no further breakdown e.g. in emissions arising from extraction and emissions arising from processing or transport. We keep the category "fugitive emissions from solid fuels", however we need to disaggregate "fugitive emissions from oil and gas" into oil and gas. To do so, we use the ratio of the sum of oil and gas emissions from the national inventory reports (NIR) submitted to the United Nations Framework Convention on Climate Change (UNFCCC, 2009) for USA, JPN, EUR and RUS; in ROW, we use the ratio of the most important emitters with NIR data available, i.e. Australia, Canada, Turkey and Ukraine. For regions where we have no NIR data available, we use the average of the above. This yields

$$\frac{Emi_{oil}^{regi}}{Emi_{gas}^{regi}} = \frac{\sum_{NIR} Emi_{oil}^{NIR}}{\sum_{NIR} Emi_{gas}^{NIR}}.$$

In AFR, the extracted fuel and also the emissions are so low, that emission factors cannot be calculated reliably. Small errors in measuring the emissions lead to large deviations in calculated emission factors. Therefore we use the same emission factors as for MEA. The same holds for JPN: There is so little coal extraction, that emission factors cannot be calculated reliably. Since Japan has the lowest emission factors for gas and oil, we use the minimum of the other regions for coal. Table 3 shows a comparison of emissions from EDGAR, NIR, and those calculated with our derived emission factors, all for the year 2005. The total emissions are in good agreement. It also shows the emission factors we derived.

1.2 CH_4 and N_2O from waste

To estimate CH_4 and N_2O emissions from waste, we use a simple econometric model. Our hypothesis is that the amount of waste per capita and thus per capita emissions

Table 4: Relationship between per capita GDP and per capita CH_4 and N_2O emissions in developing and OECD countries in the years 1970-2005. α denotes the average of country fixed effects. The reported R^2 is the R^2-within.

	developing countries		OECD countries	
	CH_4	N_2O	CH_4	N_2O
β	0.2057***	0.1687***	0.5703***	0.3814***
α	-6.074***	-8.361***	-6.074***	-8.361***
R^2	0.3233	0.2647	0.3233	0.2647

*** p < 0.001
** p < 0.05
* p < 0.01

are related to economic development. As a proxy for economic development we use per capita GDP (Heston et al., 2012). GDP is always expressed in purchasing power parity (PPP). Emission data is again taken from EDGAR (2011). We performed a panel regression between per capita emissions (E^{cap}) and per capita GDP (GDP^{cap}) for all available countries. A fixed-effects estimator is used to estimate the equation

$$ln(E_i^{cap}(t)) = \alpha_i + \beta\ ln(GDP_i^{cap}(t)) + \epsilon_i, \tag{1}$$

where α_i are country-specific parameters constant in time and the error term ϵ_i is assumed to be identically and independently distributed (iid). This estimate yields the parameter β, which only distinguishes between developing and developed regions. The parameters α_i are country-specific and cannot be aggregated to regions. However they simply describe an offset and can therefore be chosen such that the regional emissions in the baseyear 2005 are correct. The parameters derived from the econometric estimate are given in Table 4. In USA, EUR and JPN, CH4 emissions from waste show a significant decline starting around 1990. In these regions, abatement measures have already been put into place. This is taken into account by using only the data from 1970 to 1990 for the regression. For the time span of our scenarios we use the emissions calculated with the linear regression as a baseline. We calculate the relative abatement for 2005 using the calculated baseline and the actual historical data. The abatement in 2005 is enforced as a minimum in the following years in all scenarios, including baseline scenarios.

1.3 CO_2 from cement production

One step in the cement production process is the burning of chalk, where CO_2 is emitted in the chemical reaction

$$CaCO_3 \rightarrow CaO + CO_2$$

The amount of chalk used varies only very slightly within different types of cement. On average about 0.002 kg CO_2 per ton of cement are emitted. Since the database on the amount of cement produced in each country is weak, the CO_2 emissions can also be used to determine the cement production. EDGAR provides historical data on CO_2 emissions from cement production for each country from at least 1970 on. Our hypothesis is that the demand for cement depends on population. Furthermore, we assume investments in infrastructure which need cement to depend on the capital investments. We use the same linear regression explained in chapter 1.2, only with per capita investments (INV^{cap}) instead of per capita GDP.

$$ln(E_i^{cap}(t)) = \alpha_i + \beta\ ln(INV_i^{cap}(t)) \tag{2}$$

where α_i is region specific and constant in time and β is constant across regions. However, when looking at historical data we find that in industrialized countries cement production has saturated. A possible reason for this is that infrastructure is already built and only needs maintenance. We assume this saturation effect to happen in all regions eventually. Therefore we implement a transition from increasing emissions described by Eq. 2 to constant per capita emissions using a time-dependent transition parameter $p = \{0, 1\}$.

$$E_i^{cap}(t) = \big(1 - p_i(t)\big) * exp(\alpha_i) * exp\big(\beta *\ ln(INV_i^{cap}(t))\big) + p_i(t) * \hat{E}_i^{cap}, \tag{3}$$

where $\hat{E}$ denotes per capita emissions at the level of saturation. The transition parameter p is an s-curve shaped function of per capita investment with threshold value I^t.

$$p_i(t) = \left(1 + exp\left(-\frac{2ln(9)}{2000} * \big(INV_i^{cap} - I_i^t\big)\right)\right)^{-1} \tag{4}$$

In the United States, Europe, and Japan emissions have already stabilized. As there is no information on the level of stabilization in other regions, we assume them to adopt the level of structural similar regions. Table 5 shows parameter values derived from the econometric estimate and parameters chosen for the transition.

Table 5: Relationship between per capita GDP and per capita CO_2 emissions from cement in REMIND regions in the years 1970-2005. α denotes the average of country fixed effects.

Region	α	β	$\hat{E}$	I^t
AFR	0.0005	0.3745	0.0039	6310
CHN	0.0069	0.3745	0.0085	6310
EUR	0.0773	0	0.0060	0.1
IND	0.0013	0.3745	0.0085	15850
JPN	0.0999	0	0.0851	0.1
LAM	0.0017	0.3745	0.0039	6310
MEA	0.0036	0.3745	0.0060	3981
OAS	0.0016	0.3745	0.0060	15850
ROW	0.0058	0	0.0044	0.1
RUS	0.0701	0	0.0060	0.1
USA	0.0537	0	0.0393	0.1

2 Aerosol emissions from the energy system

We consider three types of aerosol emissions: Sulfur, black carbon (BC) and organic carbon (OC). Anthropogenic sulfur emissions are largely due to fossil fuel combustion. This accounts for 84%, emission from industrial processes (mainly production of metals) make up 13%, and open burning account for the remaining 3% (EDGAR, 2011). Emissions from industrial processes and biomass burning are exogenous and taken from the RCP scenarios (RCP6 (Fujino et al., 2006), RCP45 (Smith and Wigley, 2006), and RCP3PD (van Vuuren et al., 2007), respectively, depending on the climate target). In these scenarios, emissions from industrial processes and emissions due to fossil fuel combustion in the industry are aggregated. In REMIND emissions from fossil fuel combustion are modeled by source. To extract only process emissions, we calculate the process emission share in industry emissions from EDGAR (2011) from 1970-2008. It was constant around 40% with little variance in the last years. We take the mean value of the last 38 years and use this share of industrial emissions from the RCP scenarios. RCP emissions are not available for REMIND regions, but on a higher aggregated level. We therefore calculate regional shares of non-energy emissions from EDGAR (2011) for the year 2005 and keep them constant over time.
Emissions from the energy system, i.e. emissions due to coal, oil and biomass combustion are modeled by source.

Coal and crude oil usually contain 1-2% sulfur by weight. More than half of the global sulfur emissions arise from coal combustion and another 25% from oil combustion (Smith et al., 2001). Sulfur emissions from natural gas can be neglected in our model because it has to be desulphurized for transport in order not to damage the pipelines. This leads to very low emission factors which account for less than 1% of the total emissions. Traditional biomass contributes around 1% of global sulfur emissions (Smith et al., 2001) and is also neglected.

In 1995, around 42% of global BC emissions came from open burning of forests, savannah, waste, and agricultural residue. The remaining 58% came from contained combustion of coal, biofuel, and transportation fuel, with biofuel accounting for 20% and fossil fuels for 38% (Bond et al., 2004). OC emissions arise mainly from open burning (74%). Fossil fuel and biofuel contribute 7% and 19%, respectively.

Exposure to high levels of SO_2 can cause respiratory problems, chronic bronchitis, heart diseases and exacerbate existing asthma (Anderson et al., 1997; Hedley et al., 2002; Sunyer et al., 1997). High levels of indoor smoke can cause heart and lung diseases and are held responsible for millions of premature deaths in developing countries (Rao et al., 2012). Because of these negative impacts, governments have intervened to decrease aerosol emissions. Scrubbers can reduce SO_2 emission factors e.g. in coal power plants substantially and are therefore widely used by now, at least in new power plants. Another possibility to reduce aerosol emissions is to shift to conversion technologies with lower specific emissions like IGCC (integrated gasification combined cycle) power plants instead of conventional pulverized coal power plants for the conversion of coal to electricity. Due to this technologies, power plants no longer emit the full sulfur content of the specific fuel and BC and OC emissions are also declining. Emission factors have already substantially declined in OECD countries and are very likely to continue to do so in all world regions. This is reflected in time-dependent modeling of aerosol emission factors. We take up Steve Smith's approach for modelling SO_2 emission factors and use it for BC and OC, too.

2.1 Dependency of emission factor on affluence

Smith (2005) formulates a connection between affluence, measured in GDP per capita, and decline of sulfur emission factors. The maximal or uncontrolled emission factors EF_{max} [Tg S / TWa] are determined by sulfur content of fuel and ash retention. A certain fraction of these emissions can be controlled with end-of-pipe technologies. The maximum level of control f_{max} depends on technology and fuel. The percentage of controlled emissions increases with increasing GDP per capita. This function is s-shaped and defined by the mid-point $GDPcap_0$, where half of the possible reductions are realized, and the range τ in which 90% of the reductions occur. The functional form of the fraction of controlled emissions $f_{control}$ is

$$f_{control}(t) = \frac{f_{max}}{1 + exp\left(-\frac{c}{\tau}\left(GDPcap(t) - GDPcap_0(t)\right)\right)}, \tag{5}$$

where c is a constant equal to 2 ln(9) = 4.394. This yields the emissions factor $EF(t) = EF_{max} * (1 - f_{control}(t))$. We use this approach to calculate time-dependent, region- and technology-specific emission factors for sulfur, BC, and OC.

Table 6: Key parameters for evolution of emission factors.

Region	$GDPcap_0$ [k\$/cap]	τ [k\$/cap]
AFR	10	12
CHN	11	12
EUR	25	12
IND	12	12
JPN	12	5
LAM	20	20
MEA	17	12
OAS	12	12
ROW	15	12
RUS	14.5	12
USA	32	25

2.2 Parameter values

We have to determine four parameters for each technology and fuel: The uncontrolled emission factor EF_{max}, the maximum level of control f_{max}, the per capita GDP where half of the possible emission reduction is realized $GDPcap_0$ and the range τ in which 90% of the reductions occur. Since data is not available for each REMIND technology, we only distinguish the four sectors power plants, residential energy use, industry and transport.

Values for τ and $GDPcap_0$ are based on Smith et al. (2005) (Table 6). They vary by region, but do not depend on fuel or technology. For USA, JPN and EUR we had to adapt the original values slightly to be able to reproduce 2005 emission data. In regions which have not yet reached $GDPcap_0$, we adapted the value to take into account technological diffusion. In Smith's approach, $GDPcap_0$ decreases at 0.075% per year due to technological diffusion. At the point in time $GDPcap_0$ is reached, it has already fallen to a lower level. To reduce numerical complexity, we keep $GDPcap_0$ constant at this lower level instead of the initial value, such that at the time a region achieves its $GDPcap_0$ our value equals the value in Smith's approach.

The maximum level of control f_{max} is assumed to be only fuel and technology dependent. It is kept constant over region and time. Values for f_{max} are taken from Smith for SO_2 (see Table 7) and based on Klimont et al. (2002) for BC and OC (Table 8).

EF_{max} depends on the fuel type and, in case of BC and OC, on the combustion process. For each aerosol and fuel type it is specified for power plants (energy), residential energy use (res), industry (ind) and transport (trans) (see Table 7 and Table 8 for parameter values). Since the sulfur content of coal varies between regions,

uncontrolled emission factors for sulfur are also region specific.
To calculate emission factors, it would be best to divide emissions of all fuel types and sectors by the respective activity data. However, emissions disaggregated by region and fuel are not available. Smith et al. (2001) provides disaggregation of sulfur emissions by fuel type and region. EDGAR (2011) provides disaggregation by source and region. For BC and OC we have only global emission data by fuel or by sector from Bond et al. (2004). The problem now is to find emission factors such that our emissions match all inventories.
One problem is that REMIND aggregates the industrial and the residential sector. To be able to report these sectors separately, we disaggregate them using fixed shares. Industry shares are calculated based on ENERDATA (2012), which provides coal, oil, and biomass consumption totals and industry.
To determine uncontrolled emission factors for sulfur we use sulfur content as a proxy. According to Smith et al. (2011), the sulfur content in coal and oil is usually 1-2% by weight. 1% sulfur content by weight would yield uncontrolled emission factors of about 13 Tg S/TWa for coal, if we assumed an average energy content of 24 MJ/kg. If we assume 45 MJ/kg for oil, we get 7 Tg S/TWa. We vary the uncontrolled emission factors in the range of the sulfur content such that regional emissions in 2005 match historic emissions by EDGAR.
When using sulfur content as a proxy, we have to take into account that a fraction of the sulfur remains in the ashes. Following Smith et al. (2001), we assume a 30% reduction in emissions from lignite and a 5% reduction for hard coal due to ash retention. We use IEA (2009) data to determine the share of hard coal and lignite in each region and calculate an aggregate ash retention as weighted average. For the buildings sector we adopt Smith's minimal value of 10% for all regions. From this we calculate sulfur emissions E in each region r, sector s, and timestep t as

$$E(t,r,s) = EF_{max}(r) * (1 - f_{ash}(r,s)) * (1 - f_{control}(r,t)) \,, \tag{6}$$

where f_{ash} is the fraction of ash retention and $f_{control}$ is the fraction of controlled emissions.
In REMIND, we have to use primary energy demand to calculate sulfur emissions, because final energy would already contain biomass, e.g. in form of bioliquids. However, on a primary energy level, oil is converted using refineries. This technology does not distinguish between transport fuels and heating oil. We separate transport fuels and heating oil by calculating the share of transport fuels time- and region-specific on a final energy level as (fepet + fedie)/(fepet + fedie + fehos). This transport share is updated after every negishi iteration. The remaining oil is heating oil, which is divided between industry and residential use with the industry shares derived from ENERDATA (2012).

For BC and OC it is the other way around. Here we need to use final energy specifically to include synthetic fuels. Since carbonaceous aerosols are created in the combustion process, emission factors should be similar between oil and synthetic liquids. Heating oil is divided between industry and transport as for sulfur. Since data availability is much worse than for sulfur, we do not vary uncontrolled emission factors regionally. Also, in case of sulfur the sulfur content in fuels varies regionally,

Table 7: Uncontrolled aggregate sulfur emission factors EF_{max} in [Tg S / TWa] for all regions and sectors and maximum level of emission control f_{max} for all sectors (constant for all regions).

	Coal			Oil			
Region	Energy	Ind.	Res.	Energy	Ind.	Res.	Trans.
AFR	14.3	14.3	13.5	8	5	5	4
CHN	9.5	9.5	9	8	5	5	3.5
EUR	16.3	18.1	18	8	5	5	5
IND	9.4	9.4	9	7	5	5	6
JPN	15.2	15.2	14.4	15	5	7	6
LAM	16.9	17.1	16.2	18	7	7	3
MEA	15	14.5	14.4	20	10	5	3.5
OAS	8.3	8.5	8.1	7	5	5	3
ROW	17.3	18.1	18	12	7	7	3.5
RUS	10.5	10.9	10.8	15	7	7	4.5
USA	18.7	19	18	15	5	5	6
f_{max}	0.9	0.45	0.75	0.75	0.75	0.75	0.9

but carbonaceous aerosol emission depends on the combustion process only. Therefore there is no reason for regional differences. Bond et al. (2004) and Bond and Sun (2005) give ranges for emission factors. Bond et al. (2007) shows emissions by fuel. In Bond et al. (2004) global emissions are disaggregated by fuel and sector. We vary sectoral emission factors in the given ranges such that these inventories are met. Table 8 shows the exact values.

2.3 Pollution control costs

End-of-pipe pollution controls exist, that significantly lower air pollutant emissions. For different sectors, different options are available, e.g. flue gas desulphurization for coal power plants, emission controls for vehicles as employed in the EURO-IV / EURO-V standards. US EPA provides data for the average annual cost effectiveness for various control measures. Table 9 lists all relevant REMIND sectors and the according pollution control costs.

The pollution control costs C are calculated for each region $regi$, technology te, and pollutant p as

$$C(t, regi, te, p) = \left[EF_{2005}^{glob}(p) - EF(t, regi, te, p)\right] * E(t, regi, te, p) * cost(t, regi, te, p), \tag{7}$$

where EF_{2005}^{glob} denotes the mean global emission factor in 2005, EF the actual emission factor, E the specific emissions, and $cost$ the average annual cost effectiveness given in Table 9. Since costs are given in $ per abated ton, we have to calculate abated emissions with respect to some baseline. We chose mean global emissions in 2005 as a reference value, because otherwise additional costs would show up already

Table 8: Uncontrolled aggregate BC and OC emission factors EF_{max} in [Tg BC / TWa] and [Tg OC / TWa], respectively for all regions and sectors and maximum level of emission control f_{max} for all sectors (constant for all regions).

		BC		OC	
Fuel	Sector	EF_{max}	f_{max}	EF_{max}	f_{max}
Coal	Energy	0.012	0.99	0.1	0.99
	Industry	0.7	0.5	0.4	0.5
	Residential	4	0.5	10	0.5
Oil	Energy	0.07	0.99	0.01	0.99
	Industry	0.5	0.99	0.01	0.99
	Residential	2	0.3	1	3
	Transport	0.9	0.96	1	0.96
Biomass	Energy	0.09	0.99	0.4	0.99
	Industry	0.7	0.5	2	0.5
	Residential	4	0.65	30	0.65
	Transport	0.9	0.96	0.9	0.96

in 2005. However, REMIND has been calibrated to 2005 without air pollution control costs, therefore we can assume all costs until 2005 to be already included in the model.

Table 9: End-of-pipe air pollution control options and costs. Source: US EPA (2006a) if not indicated otherwise.

REMIND sector	EPA technology	Primary pollutant	Control efficiency	Average annual cost effectiveness [$/ton]
Energy, Coal	Wet Flue Gas Desulfurization (US EPA, 2003)	SO_2	90 %	200-500
Energy, Oil	Wet Flue Gas Desulfurization	SO_2	90 %	4,524
Energy, Biomass	Fabric Filter (Pulse Jet Type)	BC	90 %	117
Industry, Coal	Wet Flue Gas Desulfurization	SO_2	90 %	1,536
Industry, Oil	Wet Flue Gas Desulfurization	SO_2	90 %	4,524
Industry, Biomass	Fabric Filter (Pulse Jet Type)	BC	90 %	117
Residential, Coal	Fabric Filter (Pulse Jet Type)	BC	99 %	117
Residential, Oil	Dry ESP-Wire Plate Type	BC	98 %	110
Residential, Biomass	NSPS compliant Wood Stoves	BC	98 %	2,000
Transportation, Oil	Diesel Retrofit (US EPA, 2006b)	PM	90 %	11,100 - 69,000

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Chapter 3

CO_2 emissions in developing countries *

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Analysis

Development without energy? Assessing future scenarios of energy consumption in developing countries

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ABSTRACT

We analyze the relationship between economic development and energy consumption in the context of greenhouse gas mitigation. The main contribution of this work is to compare estimates of energy thresholds in the form of minimum energy requirements to reach high levels of development with output projections of per capita final energy supply from a group of integrated assessment models (IAMs). Scenarios project that reductions of carbon emissions in developing countries will be achieved not only by means of decreasing the carbon intensity, but also by making a significant break with the historically observed relationship between energy use and economic growth. We discuss the feasibility of achieving, on time scales acceptable for developing countries, both decarbonization and the needed structural changes or efficiency improvements, concluding that the decreases in energy consumption implied in numerous mitigation scenarios are unlikely to be achieved without endangering sustainable development objectives. To underscore the importance of basic energy needs also in the future, the role of infrastructure is highlighted, using steel and cement as examples.

1. Introduction

With the publication of the United Nations Development Program report, "Our Common Future" in 1987 (WCED, 1987), impetus was given to the world community to address in an integrated manner the interlinked challenges of environmental degradation and sustainable development. In many ways it is the current world energy system that is at the nexus of these two issues. On the one hand – even though not incorporated directly in the Millennium Development Goals (MDG) – energy is undoubtedly essential for human development (GNESD, 2007). On the other hand, supply of energy in the past has been strongly connected to the combustion of fossil fuels and emission of GHG. From a developing country perspective, it is essential to understand how poverty alleviation and acceptable development levels that go beyond pure subsistence can be reached; at the same time the necessity of leap-frogging unsustainable development pathways that have been witnessed by developed countries in the past is highly obvious (World Bank, 2010).

Incorporating GHG mitigation into the discussion of sustainable development and requirements for energy system transformation implies a need for analyzing various scenarios for future greenhouse-gas emission pathways. To this end, integrated assessment models (IAMs) project future emissions, given a set of assumptions about population, economic growth and technological progress, and starting with data about the current state and past trends in the energy system. IAMs allow comparisons between baseline scenarios designated as business-as-usual (BAU) and those in which GHG mitigation policies are assumed (POL).

A broad range of studies is available in which mitigation costs in terms of foregone GDP or consumption[1] are evaluated under different circumstances (e.g. Clarke et al., 2009; Edenhofer et al., 2006, 2010; Luderer et al., 2012a; Weyant et al., 2006). Generally, macro-economic costs are found to be moderate in a first-best world with full techno-economic flexibility. This finding crucially depends on the ambitiousness of the climate target, assumed technological change, availability of technologies and the starting point of global mitigation efforts.

Analyses by IAMs have been at the heart of recent IPCC reports as for example the Fourth Assessment Report (AR4) (Fisher et al., 2007) or the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (Fischedick et al., 2011) and will continue to play an important role in the Fifth Assessment Report (e.g. Kriegler et al., 2012). Given the central role of IPCC assessments of published literature for international climate policy negotiations, it is important that IAMs provide robust estimates of future mitigation costs and transition pathways.

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[1] IAMs start only slowly to take broader aspects of development and sustainability into account, see e.g. Urban et al. (2007), van Vuuren et al. (2007), Bollen et al. (2009), and van Ruijven et al. (2008).

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When evaluating possibilities to avoid carbon emissions in the future, two options are at the heart of the current debate; cutting carbon-intensity by promoting carbon-free technologies like renewable energy technologies, nuclear energy or CCS, and improving energy intensity, either by higher levels of efficiency or through structural change.

Past studies have critically assessed the robustness of scenario analyses with respect to assumed energy- and carbon-intensity improvements. Pielke et al. (2008) argue that scenarios assessed for AR4 systematically overestimate the role of energy intensity improvements in the future and at the same time underestimate the carbonization dynamics of newly industrializing countries, like China or India.

In this paper we assess the role of energy consumption in scenarios of the future, particularly highlighting the essential role of energy in development processes. We start by evaluating the role of energy for human development by drawing on existing literature. We conjecture that economic development very likely requires a minimum level of energy.

We continue by asking whether energy consumption, as calculated in IAMs, is consistent with how energy has been related to development in the past.[2] We synthesize our insights from the analysis of historic patterns with the output projections of integrated assessment models (IAMs), particularly the ReMIND-R model, under both BAU and GHG mitigation scenarios. We evaluate how the relationship between energy use and economic growth is represented in these models, particularly for developing regions.

To better understand the nature of energy requirements in growth processes, we look at the role of infrastructure and related energy requirements. By means of extrapolation of historical patterns regarding the relationship between economic variables and infrastructure, we aim to provide a rough estimate of a lower bound of minimum requirements for energy use in the future.

Our analysis raises doubts that the role of energy in development processes is adequately considered in IAMs. We show examples in which multiple technological pathways are able to achieve a given global mitigation target according to the output of an IAM, but where the application of additional sustainability criteria, i.e. energy access tends to call into question the internal consistency of these mitigation pathways. These results may serve as a starting point for a discussion about the appeal of some of these pathways, in particular for developing countries. Therefore, we conclude with a discussion of our results with respect to their implications for future modeling exercises as well as climate policy, arguing that additional goals for sustainable development, such as access to energy, are closely related to economic development and hence must be included in the analysis of energy system transformation pathways.

2. Energy and Human Development

A substantial literature shows a robust positive correlation between per-capita income and energy consumption, at least at relatively early stages of development (e.g. Grübler, 2008; Schäfer, 2005). It has repeatedly been argued that due to increased demand for a clean environment and structural economic change, environmental pressures might decrease with rising incomes. However, this so-called 'Environmental Kuznets Curve' relationship that has been derived for certain local pollutants, such as SO_2 and PM (e.g. Grossman and Krueger, 1995; Selden and Song, 1994), does not seem to apply for energy use or CO_2 emissions (Luzzati and Orsini, 2009; Stern, 2004).

Consequently, the question of whether there is a minimal amount of energy necessary to allow for economic development arises. We consider here some bottom-up investigations of energy consumption patterns. A first, qualitative consideration would be that households must have access to some forms of energy for cooking food, and depending on the climatic zone, to energy for heating their homes. Beyond this 'direct' energy use, there are also 'indirect' needs for energy, e.g. to produce consumer goods or build up infrastructure (such as buildings and roads), which we will discuss in more detail in Section 4 of this paper.

One of the earlier works to look at this issue is that of Krugman and Goldemberg (1983) in which they determine a threshold of ~45 GJ/year for development to "acceptable" levels for Latin America, Africa and Asia. Their results come from bottom-up data, and include both commercial and non-commercial energy sources. A later paper by Goldemberg et al. (1985) attempts to determine energy needs for the future, given the ability to access an array of technologies to significantly enhance energy efficiency. Under those conditions, the authors arrive at a figure of approximately 1 kW as the rate of minimum average energy consumption (equivalent to ~31 GJ/year), considering both direct and indirect energy consumption, using Western Europe and Japan in the early 1970s as the target level for acceptable development. Considering only rural households, Pereira et al. (2011) set a level of ~10 GJ/year of direct energy consumption as a poverty threshold, using surveys of rural Brazilian households. This is not necessarily in conflict with the other references above, since indirect energy consumption can represent 50% or more of total energy, as shown by input–output analysis for Indian households, where similar primary energy consumption levels were found (Pachauri and Spreng, 2002), and because of a difference in defining the threshold (poverty vs. acceptable living standard).

IAMs also have begun to include consideration of energy access and minimal thresholds using a bottom-up model specifically developed to address the question of household energy needs; Daioglou et al. (2012) and van Ruijven et al. (2011) investigate regional variations in final household energy needs and find, although with large variations, a rough average in line with 10 GJ/capita. Energy access is the focus of the MESSAGE-Access model (Ekholm et al., 2010; Narula et al., 2012); current levels of household energy use in India, for example, are found to be less than 10 GJ per capita. Analyses of IAM output for different regions (China and India) and societal groups (urban vs. rural), show the same broad picture for household energy consumption (Krey et al., 2012).

A key point we wish to make with this paper is to make a distinction between minimal energy threshold for emerging from a state of absolute poverty, and the amount of energy needed to achieve high or very high development levels, e.g. in terms of the Human Development Index (HDI). A consistent feature of the literature is that energy needs for households continue to increase during the development process. If climate policies starkly reduce the amount of per capita final energy available for a developing country, there must be a clear description of how this is to be achieved, given large amounts of historical experience that indicates otherwise. Furthermore, the emphasis in the literature cited thus far has not been on a direct comparison between energy needs under business-as-usual vs. climate policy scenarios.

With respect to sustained economic development, it is clear that monitoring GDP growth rates alone is an insufficient condition for ensuring development. Broader measures of social and economic development such as the HDI,[3] although not without conceptual difficulties (see

[2] Please note that IAMs usually report consumption or GDP as development indicators and do not take broader concepts of development into account. We view GDP as at best a rough proxy since alternatives are not available in the IAM literature.

[3] The HDI is defined as a geometric mean of three different components of human well-being: life expectancy, education, and income. The indices are relative and normalized, such that for each component the individual country component value is calculated with respect to the minimum value in the sample, and then normalized to the maximum difference found in the sample. The education dimension is in turn made up of two parts, one being the mean years of schooling, the other being the expected years of schooling. A country potentially having the highest score across all three dimensions would have an HDI value of 1.0. The income dimension of HDI is included logarithmically in the index, acknowledging the decreasing return to well-being with increasing income.

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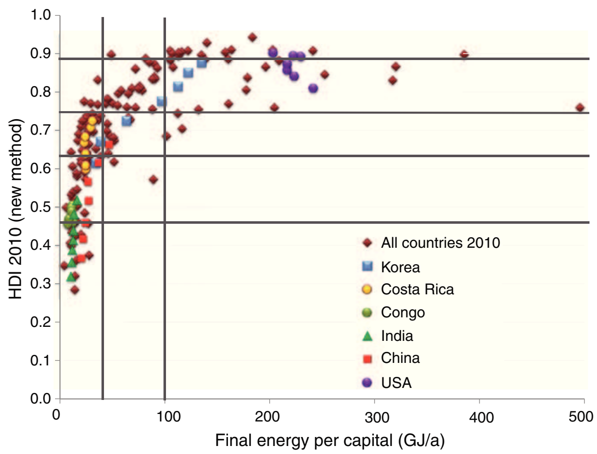

Fig. 1. Correlation of (final) energy use (IEA, 2012) and HDI (UNDP, 2012) in 2010 for 144 countries, together with the development over the period 1980–2005 for selected countries in time steps of five years. Horizontal lines indicate the separation between "very low", "low", "medium", "high" and "very high" development categories. Vertical lines indicate per capita final energy levels of 42 GJ (1 toe) per year and 100 GJ per year.

for example Böhringer and Jochem, 2007; Fleurbaey, 2009; Neumayer, 2001), provide a first step toward a more comprehensive evaluation.

In Fig. 1 we show the correlation between the Human Development Index (HDI) and energy use (here given in final energy consumption per capita in GJ/year). The United Nations Development Program (UNDP) defines five levels of development for the HDI: very low (<0.456); low (0.456–629); medium (0.630–0.741); high (0.742–0.888); and very high (>0.889–1.0) (UNDP, 2012). These levels are indicated by horizontal lines in Fig. 1.

For our purposes, the interesting feature is the correlation between HDI and per capita final energy consumption for countries in different stages of development, as shown in Fig. 1. The trend of increasing HDI being correlated with increasing energy use saturates at a fairly low level. For those societies in which per capita energy use is less than about 42 GJ/year, HDI is very likely to be below the "high" level and certain to be below the "very high" level. On the other hand, countries with per capita final energy use of >100 GJ/year are likely to have a "very high" HDI (as denoted by the second vertical line in Fig. 1) and almost certain to be at least in the "high" HDI category. Only few exceptions exist (Hong Kong and Malta being prominent examples), but they all operate in very particular environments. Another interesting point that comes from Fig. 1 is that countries having roughly the same level of economic development in the "high" and "very high" ranges as measured by HDI can have per capita energy consumption that varies by a factor of nearly ten (Martinez and Ebenhack, 2008).

In this respect we can show that results from Steinberger and Roberts (2010) evaluating the relationship between primary energy and HDI can also be replicated when looking at the actual energy consumption, i.e. final energy supply. It is obvious that a given level of minimum energy requirements for a sufficiently high development level today is not necessarily stable, i.e. it could be decreased in the future. Extrapolating threshold functions for primary energy observations of the past, Steinberger and Roberts (2010) find minimum future primary energy levels for high development levels to decrease — a result that can also be expected when looking at final energy levels. It is however questionable whether and to what extent historical trends can be expected to continue in the future. In order to shed light in this question, it must be better understood how thresholds – here understood as minimum energy requirements for high or very high development levels – can be explained. Infrastructure, which we discuss in Section 4 might provide one potential explanation for the existence of thresholds.

3. Energy, Development and Scenarios of the Future

In the following we assess a broader set of IAMs with respect to the question of how growth and final energy supply are projected to develop in future scenarios with and without mitigation of GHG emissions. As they are able to represent complex interrelations between the energy, socio-economic and climate systems, IAMs are a powerful tool for describing how growth and energy supply develop in the future. We will compare our hypothesis as formulated and backed by bottom-up analysis in Section 2 with top-down model results, before we discuss the implications of the results for (a) climate policy and (b) the consistency of IAM results in general. As IAMs usually do not take broader concepts of development into account (although are starting to do so, as discussed above), we will refer to GDP or consumption per capita in the following, acknowledging the difficulties that are connected to this indicator. However, particular for low income levels, GDP per capita is strongly correlated with the HDI (Islam, 1995).

3.1. Energy and Development from a Model Perspective

Using the empirical correlations above as a basis, and recognizing that countries or regions in different stages of development will have differing goals for energy use, we compare final energy consumption under baseline and climate-policy scenarios for several different groups of countries, based on scenarios used by two recent model comparison exercises, ADAM (Edenhofer et al., 2010) and RECIPE (Luderer et al., 2012a). We thus can capture a broad range of different model philosophies and assumptions regarding model inputs, e.g. with respect to the role of technological change. Edenhofer et al. (2010), Luderer et al. (2012a), Knopf et al. (2009), Tavoni et al. (2012) and Jakob et al. (2012a) give a more detailed description of the assessment framework. A variety of models has been used in these exercises, i.e. ReMIND-R (Bauer et al., 2012; Leimbach et al., 2010), MERGE-ETL (Kypreos, 2005; Kypreos and Bahn, 2003), IMAGE/TIMER (Bouwman et al., 2006; van Vuuren et al., 2006), POLES (European Commission, 1996), IMACLIM-R (Sassi et al., 2010; Waisman et al., 2012) and WITCH (Bosetti et al., 2006; De Cian et al., 2012). We organize available scenarios into clusters based on climate targets as defined by the IPCC (2007): baseline scenarios with atmospheric GHG concentrations higher than 710 ppm CO_2-eq; so-called category 3 & 4 scenarios with equilibrium atmospheric GHG concentrations between 535 and 710 ppm CO_2-eq; and category 1 & 2 scenarios, which result in concentrations lower than 535 ppm CO_2-eq.[4]

The results shown in Fig. 2 represent the output of six IAMs for business-as-usual (BAU) and for two categories of climate policy scenarios. The boxes and bars represent the range of values from the different model runs, with the median of all model runs given by a horizontal bar, and the ends of the bars indicating the extreme values of model output. The boxes correspond to the interquartile range (25th–75th percentile). We look at two points in time, 2030 (black boxes) and 2050 (red boxes) and different regions. The left-hand column shows the aggregate of all Non-Annex I[5] countries (a), China (b) and India (c), while the column on the right shows results for all Annex I countries (d), and for the US (e) and Europe (f). Note that across the different models the aggregation into regions is not necessarily harmonized and slight variations might occur.

[4] In the IPCC AR4 stabilization categories are defined as follows: 1: 445–490 ppm CO_2 eq; 2: 490–535 ppm CO_2 eq.; 3: 535–590 ppm CO_2 eq; 4: 590–710 ppm CO_2 eq; 5: 710–855 ppm CO_2 eq; 6: 855–1130 ppm CO_2 eq.

[5] We refer to Annex I of the United Nation's Framework Convention on Climate Change (UNFCCC), which includes the industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992, plus countries with economies in transition, including the Russian Federation, the Baltic States, and several Central and Eastern European States.

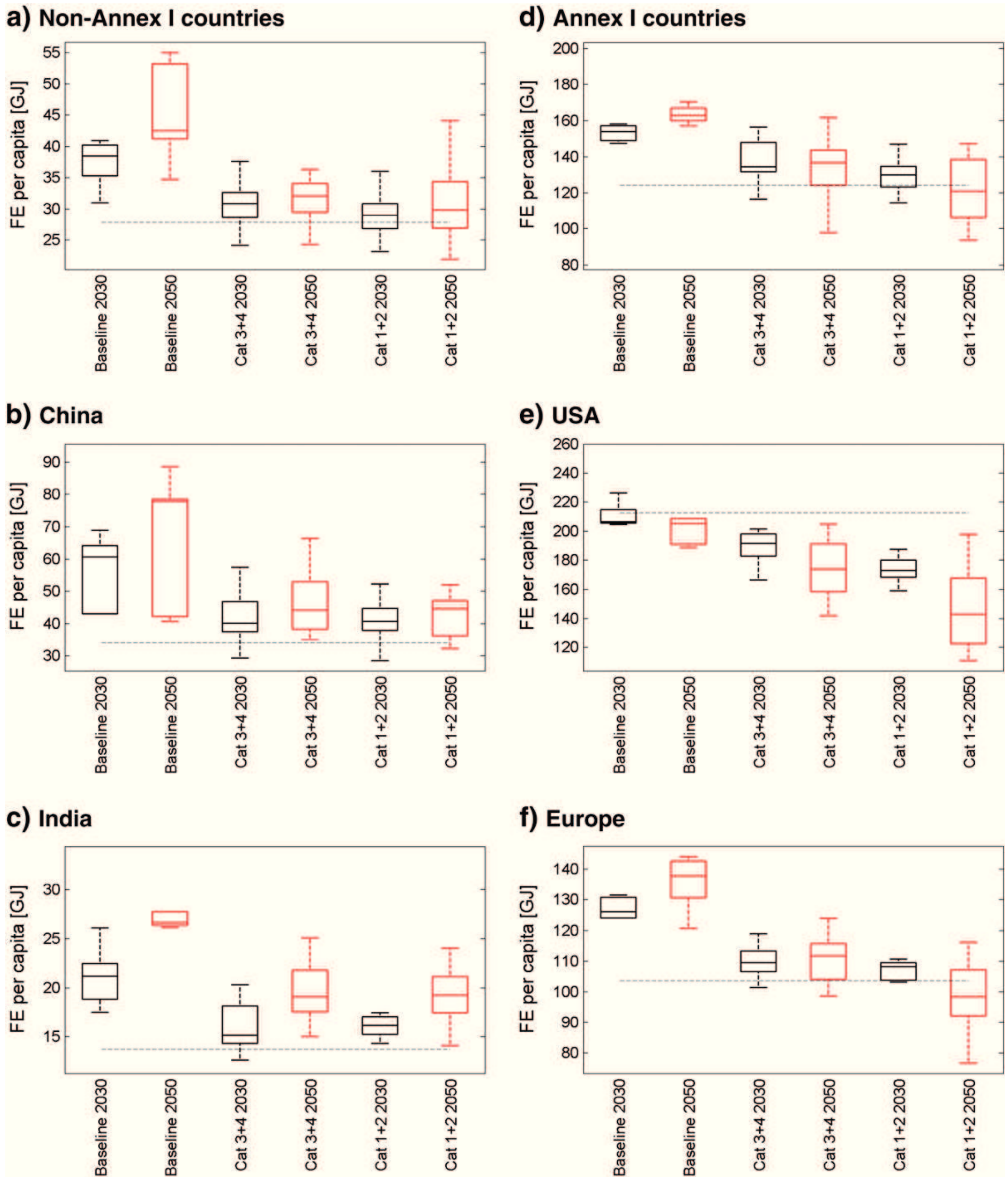

Fig. 2. Final energy use per capita per year (in GJ) in all Non-Annex I countries (a), all Annex I countries (b), China (c), the US (d), India (e) and Europe (f) for different scenario categories as defined by the IPCC, i.e. baseline scenarios, category 3 and 4 scenarios and low stabilization (category 1 & 2) scenarios. The black boxes assess data for 2030, the red boxes assess data for 2050. The thick line corresponds to the median, the boxes correspond to the interquartile range (25th–75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. The dotted horizontal line indicates the per capita FE level in 2005. Please note different scales.

From Fig. 2 we can derive three major insights: First, we note that per capita final energy consumption decreases significantly in the policy cases with respect to the BAU case for all regions, falling back to approximately today's levels by 2030. Second, while in the baseline scenarios, for Non-Annex I countries the 40 GJ/year threshold seems to be within reach and for China it is already crossed in 2030 for most models,[6] the aggregate of Non-Annex I countries remains far below that threshold in mitigation scenarios. There is a slight trend toward increasing energy consumption between 2030 and 2050 in the policy scenarios in all regions; however, it remains far below levels that are reached without GHG mitigation. In Annex I countries including Europe and the USA as well as in Non-Annex I countries, final energy consumption per capita is lower in low stabilization (categories 1 and 2) scenarios compared to medium ones (categories 3 and 4). Third, relative reductions between baseline and policy cases are higher in Non-Annex I countries compared to Annex I countries in all cases (see also Table 1); hence, despite much lower per capita FE consumption levels, models tend to project energy demand in developing countries to be more elastic than in developed countries.

[6] Analysis of recent data suggests that China has crossed the threshold already.

Table 1
Reduction of FE per capita between mitigation and baseline scenarios in 2030 and 2050 in Annex I and Non-Annex I countries.

	2030				2050			
	Categories 3 & 4		Categories 1 & 2		Categories 3 & 4		Categories 1 & 2	
	Annex I	Non-Annex I	Annex I	Non-Annex I	Annex I	Non-Annex I	Annex I	Non-Annex I
Median	11%	14%	14%	20%	18%	21%	24%	27%
Mean	12%	15%	15%	20%	21%	24%	25%	28%
Min	1%	1%	7%	9%	4%	4%	10%	11%
Max	26%	38%	24%	30%	50%	52%	39%	46%

Exploring a bit further, Fig. 3 shows annual changes in energy- and carbon-intensity levels in mitigation scenarios of different ambitions in the period from 2010 to 2030. When looking at final energy- and carbon-intensity reductions in mitigation scenarios compared to BAU scenarios (Fig. 3a and b), Non-Annex I countries show reductions in energy intensity at least as high as Annex I countries in both low (category 1 & 2) and medium (category 3 & 4) stabilization targets.

When turning to absolute reduction rates (see Fig. 3c and d) annual reduction rates of final energy intensity of GDP are systematically higher in developing countries than in Annex I countries. With respect to carbon intensity, no major differences can be found, i.e. annual changes are of a comparable order of magnitude in both income groups. Even though Non-Annex I countries start from higher initial values of energy intensity the result is remarkable, as those countries can be expected to undergo structural changes that have been energy intensive in the past. For instance, for low-income countries economic growth goes hand in hand with an increasing share of industry in total production, which in general displays higher energy intensity than e.g. agriculture or the service sector (Schäfer, 2005). Hence, structural economic change toward more energy-intensive activities could – at least to some extent – counterbalance decreases in economy-wide energy intensity triggered by efficiency improvements (see e.g. Zhao et al., 2010 for the case of China).

The results from the model comparisons can be interpreted in different ways: On the one hand, decreasing absolute FE levels as well as high energy intensity reductions could simply highlight the need for improved energy intensity across all countries and income groups. However, in the light of our results in Section 2 they also could hint at a possible overestimation of realistic energy intensity improvements in developing countries. Even though IAMs are generally designed to study longer-term changes, it is important to evaluate shorter-term trends and potential for major breaks with the past that are important for questions related to development. It is important to note that models make different assumptions on the drivers

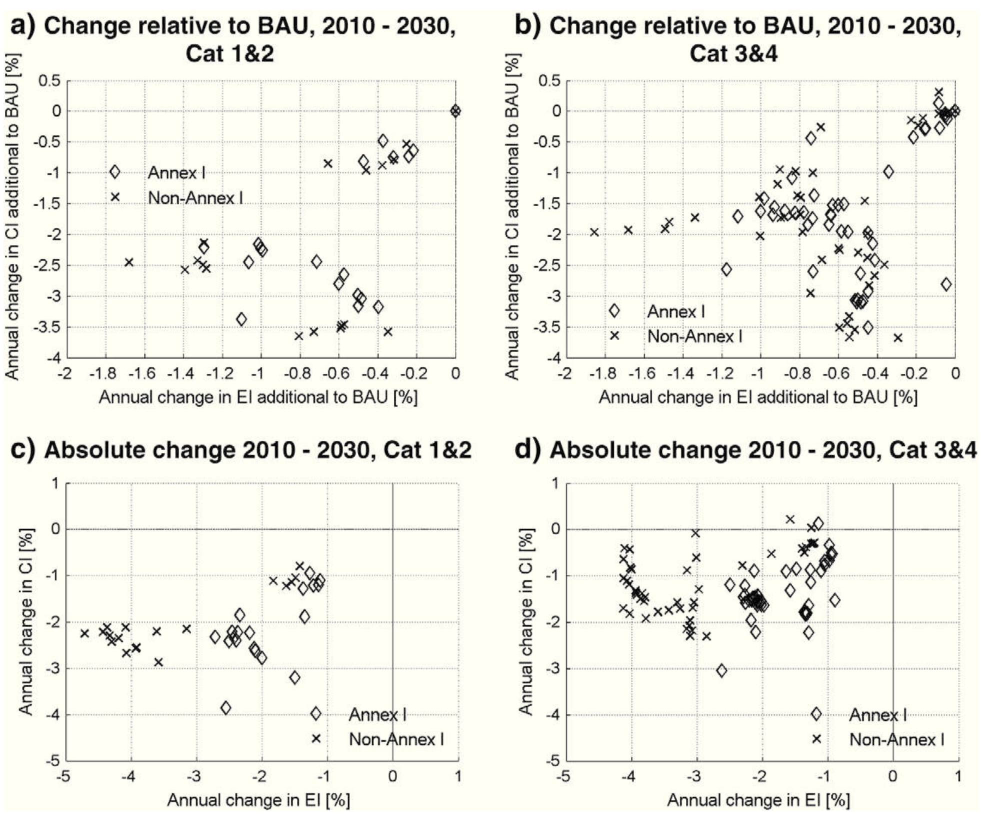

Fig. 3. Annual change in carbon intensity of energy and energy intensity of GDP for the period 2010 to 2030 in scenarios of the future for Annex I and Non-Annex I countries for category 1 & 2 (a) and category 3 & 4 (b) scenarios as well as changes compared to the respective BAU scenarios for category 1 & 2 (c) and category 3 & 4 (d) scenarios in percentage points.

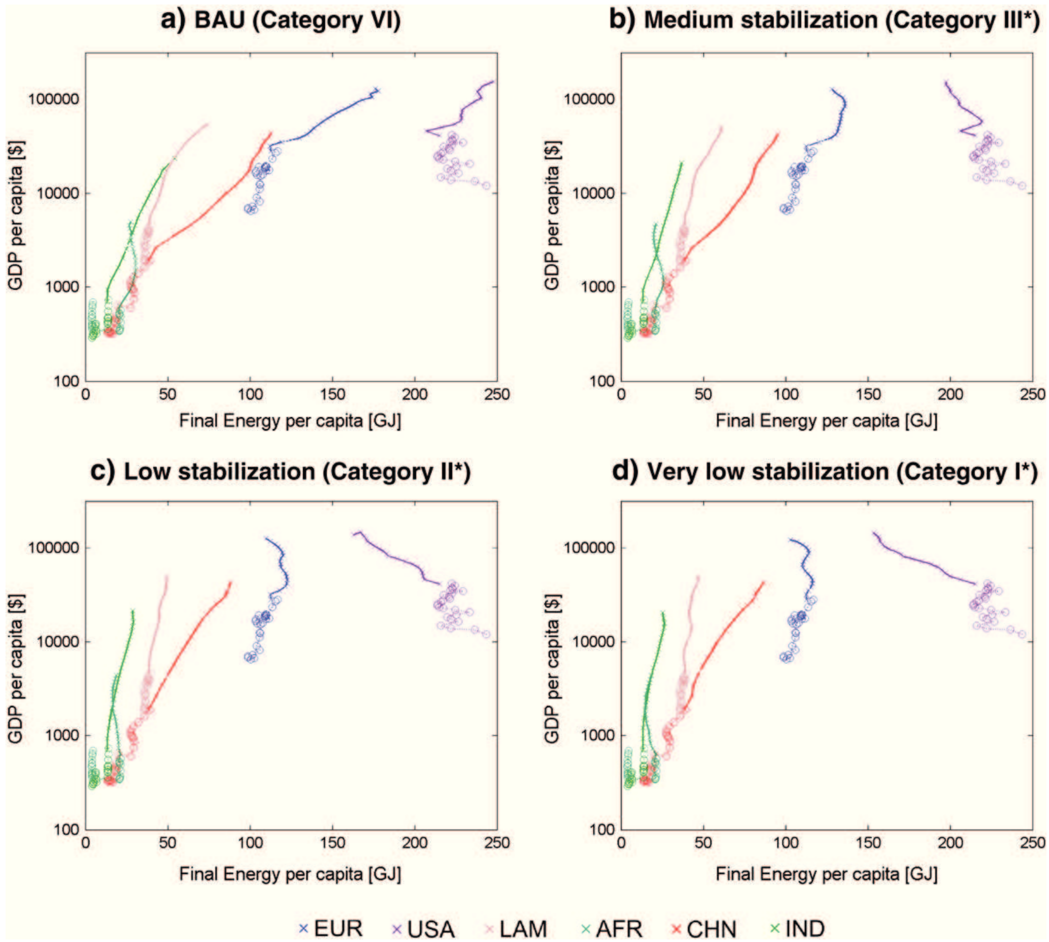

Fig. 4. GDP per capita over final energy per capita for selected regions. Circles indicate historic data (based on Penn World Tables 2009), while crosses indicate ReMIND-R model results for different IPCC stabilization categories. *Stabilization scenarios shown here are calculated by using scenarios with progressive carbon taxes increasing by 5% per annum from 2010 with initial levels of US $10, US $30 and US $50, respectively.

of energy demand, and the mechanisms leading to energy intensity improvements under climate policy. For instance, in models with explicit vintage structure, emerging economies with high growth rates and young capital stocks could be faster in adopting energy efficient technologies than established industrialized countries with old vintage structures. A dedicated model comparison would be required to dismantle these underlying dynamics, which is beyond the scope of this study. Instead, we further examine the results of the ReMIND-R[7] model in higher temporal and regional detail.[8]

Fig. 4 shows per capita GDP in 2005 US$ as a function of final energy consumption per capita in GJ[9] for four different scenarios, which represent climate targets of varying ambition. These targets are implemented by using carbon taxes, i.e. one scenario where no carbon tax is implied, defined as the business as usual scenario (BAU), and three scenarios with initial tax levels of $10, $30 and $50 per ton of carbon, which all increase by 5% per annum from 2010 in order to match the targeted levels of ambition. In our analysis we look at four developing regions, i.e. Latin America (LAM), Sub-Sahara Africa (without South-Africa), China (CHN) and India and two developed regions (Europe (EUR) and USA) with the aim of determining whether and how historic trends of energy use and welfare are reflected in our scenarios.

First, in the BAU scenario we find that historic trends are more or less reproduced for developed countries and China, which already crossed the threshold of 40 GJ per capita in 2005. For developing countries that have not crossed the threshold in 2005, historic trends are basically reproduced, i.e. increasing welfare is associated with increasing energy consumption if a certain threshold is crossed. Energy levels per capita are however lower for corresponding per capita GDP values, which could well be explained by technological improvements and leapfrogging very energy-intensive processes.

Second, if the stabilization level remains relatively moderate, developing countries do not seem to show a fundamentally different behavior than in the BAU case. On the other hand, in developed countries efficiency improvements are realized and energy consumption per GDP decreases significantly.

Third, for increasingly ambitious stabilization targets developing countries show a significantly different behavior. For all developing

[7] ReMIND-R couples a Ramsey-type economic growth model with a detailed bottom-up energy system model and a climate model. Please see http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/REMIND_Description_June2010_final.pdf for a detailed model description.

[8] These data are part of the set of scenarios prepared for the Asia Modeling Exercise (Luderer et al., 2012b).

[9] GDP per capita is reported on a logarithmic scale in order to make results roughly comparable to Fig. 1, where GDP per capita goes logarithmical into the calculation of the HDI.

regions but China, we can observe a decisive break with the historic trends. Final energy levels remain practically constant despite economic development. In some regions (Sub Saharan Africa (AFR), India) they even decrease initially. In India, which – in terms of GDP per capita – reaches development levels comparable to those of Europe today in the year 2100, FE per capita levels is projected to be around 25 GJ per capita, which is only slightly above today's levels and about one quarter of today's energy consumption in the EU27. Quite importantly, the per capita final energy consumption will never increase above this level during the entire century. Comparable patterns can be found in AFR and Latin America (LAM). AFR, approximately reaching today's GDP levels in LAM by the end of the century shows slightly lower FE per capita levels than LAM (in 2005) in the baseline scenario (30 GJ compared to 39 GJ per capita), but significantly lower (18 GJ per capita) levels in a low stabilization scenario. At the same time, the EU27 and the US – despite reducing final energy per capita consumption significantly – are still seen to be at levels above 100 (EU27) and 150 (USA) GJ per capita in the year 2100.[10]

To sum up, the above analysis of the IAM data indicates that climate policy is likely to reduce average per capita energy consumption in developing countries to a level that seems to be difficult to reconcile critical thresholds for development identified in Section 2. Particularly in ambitious mitigation scenarios, IAMs project energy consumption to decouple from economic growth in developing countries, suggesting that potentials for energy intensity improvements in developing countries are (at least implicitly) assumed to be higher than in developed countries. Taking into account that in recent decades developing countries that have experienced economic catch-up have by and large reproduced the energy-intensive development patterns of industrialized countries (Jakob et al., 2012) it is important to understand that the IAM results indicate a radical break of historic observations. In the light of the need for aggressive GHG mitigation, radical breaks with historic development patterns are surely needed. With respect to carbon intensity and the decarbonization of the energy system, IAMs generally put much emphasis on possible future transformations, e.g. by a detailed techno-economic description of energy systems. However, considerably less attention is given to the demand side in general, and the role of energy access for development processes in particular. Our results indicate that it deserves more attention for future modeling efforts.

4. Energy Thresholds and the Role of Infrastructure

In Sections 2 and 3 of this paper, we argue that there is a minimum level of energy needed for reaching high or very high development levels. We find that IAMs do not take these considerations into account. However, one could argue that future efficiency improvements will lower the amount necessary in the future (see for example Steinberger and Roberts, 2010). Therefore it is important to understand why we observe minimum levels of energy consumption in the past.

If we think of development beyond fulfilling basic needs, energy is inter alia also needed for the construction of infrastructure, including the use of cement and steel for buildings, railways and roads, electricity grids, etc., all of which come with a specific energy demand. The important role of infrastructure in development processes in general is well known in the literature, with the assumption generally being that there is a positive impact of infrastructure investment on economic development and growth (Gramlich, 1994). Different channels are identified as to how investments in public capital, i.e. infrastructure could impact growth (for a detailed review see Agénor and Moreno-Dodson, 2006). Most importantly, Aschauer (1989) – followed by many others – was the first to hint at the positive effects of infrastructure investments on other production inputs, as for example labor or the private capital stock. Infrastructure investments can thus increase the marginal productivity of private investments. Additionally, Calderón and Servén (2004) also highlight the positive effects of infrastructure investments on the reduction of income inequalities, particularly in developing countries.

In this sub-section we determine the role of infrastructure in development processes of the past, particularly focusing on the energy demand that comes with investments in infrastructure. We focus on the production[11] of cement and steel as major determinants of energy-use for infrastructure purposes.[12] Our starting hypothesis is that infrastructure production increases with increasing levels of income, while it might eventually saturate once a certain capital stock has been built up. Thus, our hypothesis is that in developing countries inputs required for infrastructure increase with economic growth. A stylized econometric model lends support to our conjecture that infrastructure uptake is an important component of an energy threshold. In order to be able to link historical econometric patterns of the past to the output of the integrated assessment model ReMIND-R in a second step, we keep the econometric part relatively simple. Hence, we can compare potential energy demand for infrastructure of the future with energy consumption patterns calculated by the model.

4.1. Energy for Infrastructure in the Past

4.1.1. Data

To use results from the historical analysis to provide rough estimates of future energy demand resulting from infrastructure, we aggregate all data[13] into 11 regions as defined in the ReMIND-R model. Table 2 gives a more detailed description of aggregated regions. We further cluster these regions into developed (OECD) and developing countries. However, we exclude the regions ROW and RUS from these two clusters: For ROW the ReMIND region is composed of developed and developing countries, while for RUS historical data are not sufficiently available.[14]

As macro-economic indicators we use data from Penn World tables 6.3 (Heston et al., 2009). Capital investments can be calculated from Heston et al. (2009) based on GDP (in MER). As the database on the amount of cement produced in each country is rather weak, we use production-based emissions data caused by cement (Boden et al., 2011) and use factors determined by the chemical processes involved to calculate cement production and consequently estimate the energy consumed in the process. This is possible because one step in the cement production process is the conversion of limestone to lime in the production of clinker, where CO_2 is emitted in a chemical reaction, i.e. $CaCO_3 \rightarrow CaO + CO_2$. Thus, cement production can directly be calculated from emissions, using a constant of 0.5 t CO_2/t cement (IPCC, 2000). For steel we use country disaggregated production data from IISI (2011) for the years 1980–2005 available for all steel producing countries.

4.1.2. Empirical Method

A simple econometric model is used to estimate the role of infrastructure (*INF*), i.e. cement and steel in development processes. Demand for cement or steel is expected to depend on the population (*POP*) of a country or region, as well as on economic development (*ECON*). As a proxy for economic development both per-capita *GDP* and per-capita capital investments (*INV*) are used (in two separate

[10] As in most IAMs, population is exogenously given in ReMIND-R.

[11] Using production instead of consumption data might be a weakness of the analysis; it is however necessary in order to link econometric results to model output in the next step.

[12] Note that other inputs might become more important for higher incomes, which is however not regarded here.

[13] Summary statistics for all data used can be found in the Appendix A.

[14] Note that with respect to steel production not every country produces steel, thus an aggregation of countries is useful. A similar analysis with disaggregated regions holds qualitatively similar results for cement.

Table 2
Regions as defined in ReMIND-R and corresponding world regions.

Model region	Countries[a]
AFR	Sub-Saharan Africa w/o South Africa
CHN	China
EUR	EU27 countries
IND	India
JPN	Japan
LAM	All American countries but Canada and the US
MEA	North Africa, Middle Eastern and Arab Gulf Countries, resource exporting countries of FSU w/o Russia, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states w/o Russia, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

[a] In the remainder of the paper we aggregate these regions into "OECD" countries and "developing countries" as follows: OECD countries are EUR, JPN and USA, while all other regions, but RUS and ROW are aggregated as "developing" countries. Note that singular countries in this group (i.e. South Korea and Mexico) now are actually OECD countries, but were not at the starting year of our sample.

Table 3
Relationship between capital investment or GDP, respectively, population and steel production in OECD countries and developing countries in the years 1980–2005. Note that data are aggregated to match the regional fit of the ReMIND-R model. α denotes the average of country fixed effects for OECD and developing countries, respectively. The reported R^2 is the R^2-within.

Steel	Developing countries		OECD countries	
β_{inv}		0.4435***		0.109**
		(4.7)		(2.54)
β_{GDP}	0.7051***		0.0969**	
	(5.77)		(2.09)	
γ	1.4318***	1.6423***	0.3927	0.2926
	(5.68)	(6.58)	(1.41)	(0.84)
α	−9.1858***	−11.2636***	6.6067*	8.5324**
	(−2.76)	(−3.34)	(1.95)	(2.36)
R^2	0.4185	0.3852	0.2319	0.2523

t-Values in parenthesis.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 4
Relationship between capital investment or GDP, respectively, population and cement production in OECD countries and developing countries in the years 1980–2005. Note that data are aggregated to match the regional fit of the ReMIND-R model. α denotes the average of country fixed effects for OECD and developing countries, respectively. The reported R^2 is the R^2-within.

Cement	Developing countries		OECD countries	
β_{inv}		0.5178***		0.0059
		(12.46)		(0.14)
β_{GDP}	0.6809***		−0.0644	
	(12.16)		(−1.41)	
γ	1.8685***	1.9753***	1.5216***	1.2125***
	(16.19)	(17.96)	(5.55)	(4.1)
α	−16.1634***	−16.7480***	−9.8383***	−6.1233**
	(−10.58)	(−11.29)	(−2.94)	(−1.68)
R^2	0.8163	0.8205	0.3803	0.3636

t-Values in parenthesis.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$

regressions), presuming that the latter are the decisive part of GDP driving the demand for infrastructure. A panel regression is performed between population, an economic development parameter (GDP or capital investments respectively) and the infrastructure parameter (cement or steel production). A fixed-effects estimator is used to estimate the following equation:

$$\ln\left(INF_{jt}\right) = \alpha_j + \beta \ln\left(ECON_{jt}\right) + \gamma \ln\left(POP_{jt}\right) + \varepsilon_{jt}, \tag{1}$$

where α_j are region-specific parameters constant in time and the error term ε_{jt} is assumed to be identically and independently distributed (iid). j specifies the respective region, for which country specific historic data series *INF*, *ECON* and *POP* are aggregated.[15] Eq. (1) is estimated separately for OECD countries and developing countries to allow for different functional relationships for these two country groups. The logarithmic transformation of the variables is used, with the respective coefficients therefore denoting elasticities, (i.e. the percentage change of the dependent variable upon a one percent change of the explanatory variables, ceteris paribus). By means of a student *t*-test we assess whether the coefficients are individually significantly different from zero.

4.1.3. Results

Qualitatively the results for steel and cement production inputs are broadly similar, as summarized in Tables 3 and 4. However, we note important differences between developing and developed countries.

For developing countries the estimated coefficients are all statistically significant on the 1%-level. For steel, about 40% of the observed variation is explained by the independent variables, as indicated by the R^2-within (which excludes the explanatory power of the country-specific fixed effects), while for cement it exceeds 80%.[16] The estimated elasticity of steel production with respect to capital and investments and per-capita GDP are about 0.4 and 0.7, respectively, while the elasticity with respect to population ranges between 1.4 and 1.6, depending on model specification. For cement, the former elasticities are about 0.5 and 0.7, respectively, and the latter are 1.9 and 2.

For developed countries, the estimated elasticities for steel are considerably lower than for developing countries, in the order of 0.1 for both per-capita investments and per-capita GDP, respectively. Both are statistically significant at the 5% confidence level. For cement, however, the coefficients of *GDP* and *INV* are not statistically different from zero. Finally, we find insignificant coefficients on population size for steel production, but coefficients which are significant on the 1% level for cement, with values between 1.2 and 1.5. These observations suggest that for developed countries, steel production is more strongly affected by per-capita GDP and capital investments, while for cement the population size is of higher importance.

These results support our hypothesis. In developing economies, higher per-capita GDP and capital investments are closely correlated with increased production of steel and cement. The low or statistically insignificant coefficients found for OECD countries suggest that once a certain level of development is reached, GDP or capital investments have a considerably less pronounced influence on these infrastructure-related variables. This finding supports the hypothesis of an energy threshold, as infrastructure inputs must first be provided in order to reach a decent level of development. Thus, a decreasing threshold would imply improvements in the supply of infrastructure inputs.

In this section we have presented evidence to support our hypothesis that infrastructure uptake is one explanatory element of an energy threshold. Keeping in mind that the goal of sustainable development

[15] Using panel data with a fixed-effect estimator is a common practice in the literature. See Markandya et al. (2006) or Burke (2010) for examples that employ this estimation technique to analyze the relationship between economic growth and energy use.

[16] This observation could for instance be due to the fact that steel is more heavily traded than cement, such that the latter's production is more closely aligned to socio-economic development.

should go beyond simply enabling a subsistence level of development, energy consumption will occur not only at the level of individual households, but also in the form of infrastructure accumulation. The next step is to compare the indicated minimal levels of energy consumption with projections arising from IAMs.

4.2. Infrastructure in Scenarios of the Future

As indicated in Section 4.1 we use infrastructure inputs to bolster the threshold hypothesis. Based on our results from the historical analysis we estimate the future energy demand for steel and cement production using state-of the art technology estimates as well as projections for the future from the literature as well as scenario results from the ReMIND-R model (Bauer et al., 2012; Leimbach et al., 2010).

To estimate the combined energy demand for cement and steel we use model output for capital investment from the ReMIND-R model and use the estimates from Section 4.1 together with country-specific fixed effects (reported in the Appendix A) to translate these results into steel and cement production. When looking at historical data for per capita cement and steel production, we find that it is rising in Non-Annex I countries, whereas it remains relatively stable in Annex I countries (cp. Fig. 5). We therefore conjecture that two different regimes exist. As long as infrastructure is being built up, the demand for cement and steel increases. When a certain level of per-capita GDP or capital investment is reached the demand stabilizes. Annex I countries have already been in the stable regime in 1980, the earliest date of available data. Therefore, for developing countries we assume a switch to OECD values once a developing country reaches levels of affluence comparable to developed countries in 1980. However, as Non-Annex I countries do not reach the per-capita investment levels expected for a regime change until 2050 accounting for a regime shift in this respect is not necessary.

Fig. 5 shows results for the relation between cement and steel production and capital investments both historically (shown in black) and the projections derived using the coefficients of our econometric estimates (shown in blue) to the year 2050 for different regions. Historical correlations between investments and cement and steel, respectively, are continued in the future scenario with some minor differentiations between regions that can also be observed in historic data. As an interesting side result, we find an implicit level of per capita steel and cement production in developed societies that ranges between 0.4 and 2 t for cement[17] and 0.3 and 1 t for steel.

We can use these results for the production of steel and cement to project the energy consumption required in the future. We assume that best practice technologies today use on average 5 GJ/t (de Vries et al., 2006; Taylor et al., 2006; Worrell and Galitsky, 2008; Worrell et al., 2000). Theoretically this can be lowered to the thermodynamic limit, which is estimated to be around 1.76 GJ/t (Taylor et al., 2006).[18] We use an estimate of current best practice energy use for the production of steel of 18 GJ/t (IISI, 2011), while we assume the minimum achievable energy intensity to be 2.5 GJ/t following long run estimations from de Beer et al. (1998). Implicitly we assume that cement and steel will not be substituted by other inputs of production in the future, or that future substitutes would have comparable energy intensities. The lower bounds of the ranges shown in Fig. 6 are calculated using the minimum achievable energy input for steel and cement (i.e. the thermodynamic limits) while the upper bounds are calculated with today's state of the art technologies' energy need.[19] Realistic results in the near future will be close to the upper limit of the range, while due to technological progress future specific energy consumption from cement and steel can be expected to eventually decrease and thus results closer to the lower range become more likely.

For countries that are currently developing, using historical fits leads to increasing energy demand for steel and cement until they reach comparable levels to developed countries without improvements in the

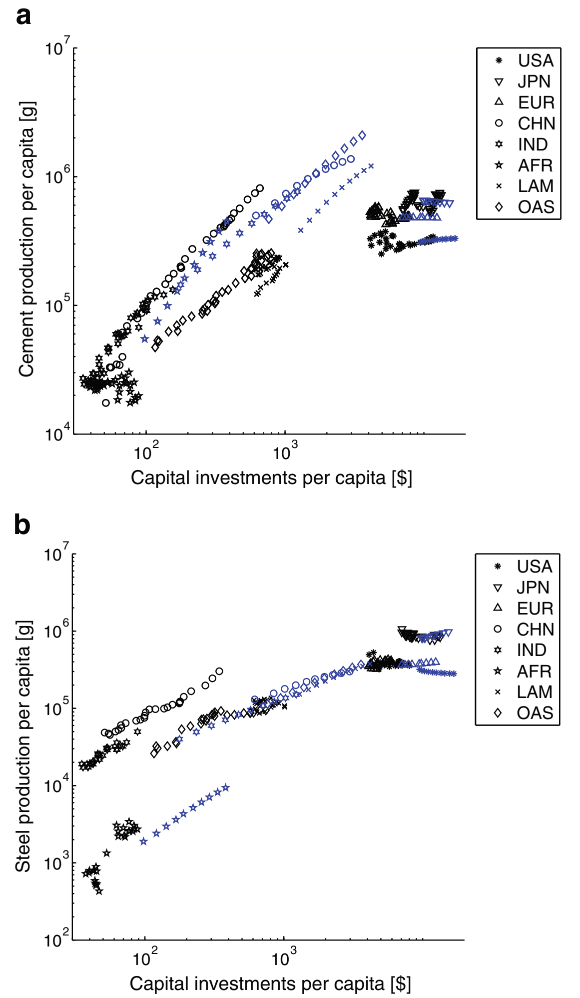

Fig. 5. Correlation between capital investments for a) cement and b) steel production on a double log scale, separated by different regions for historic data from 1980 to 2005 (black), together with scenario results from 2005 to 2050 (blue). Note that the regional aggregation follows the regions that are represented in the ReMIND model.

[17] Obviously there are large differences between country groups particular with respect to cement production. Asian countries have used significantly more cement per capita in their development process than European or North-American countries (see also Appendix C for more detailed information on cement production in selected OECD countries). We presume that differences in urban development patterns and types of buildings can explain these differences. Interestingly, newly developing countries in particular China stabilize at higher levels than previously observed. A detailed discussion of the phenomenon is however beyond the scope of this paper.

[18] The value for a ton of cement is likely to be higher, as Taylor et al. (2006) give numbers for clinker production. It is important to understand that thermodynamic limits are unlikely to be reached in reality, as other constraints (e.g. time) need to be regarded (Spreng, 1993).

[19] For cement we calculate with an energy input of 5 GJ/t for today (de Vries et al., 2006; Taylor et al., 2006; Worrell et al., 2000), which theoretically can be lowered 1.76 GJ/t in the future (Taylor et al., 2006). For steel production we estimate a current best practice energy use of 18 GJ/t (IISI, 2011), which we assume to be lowered to 2.5 GJ/t in the future.

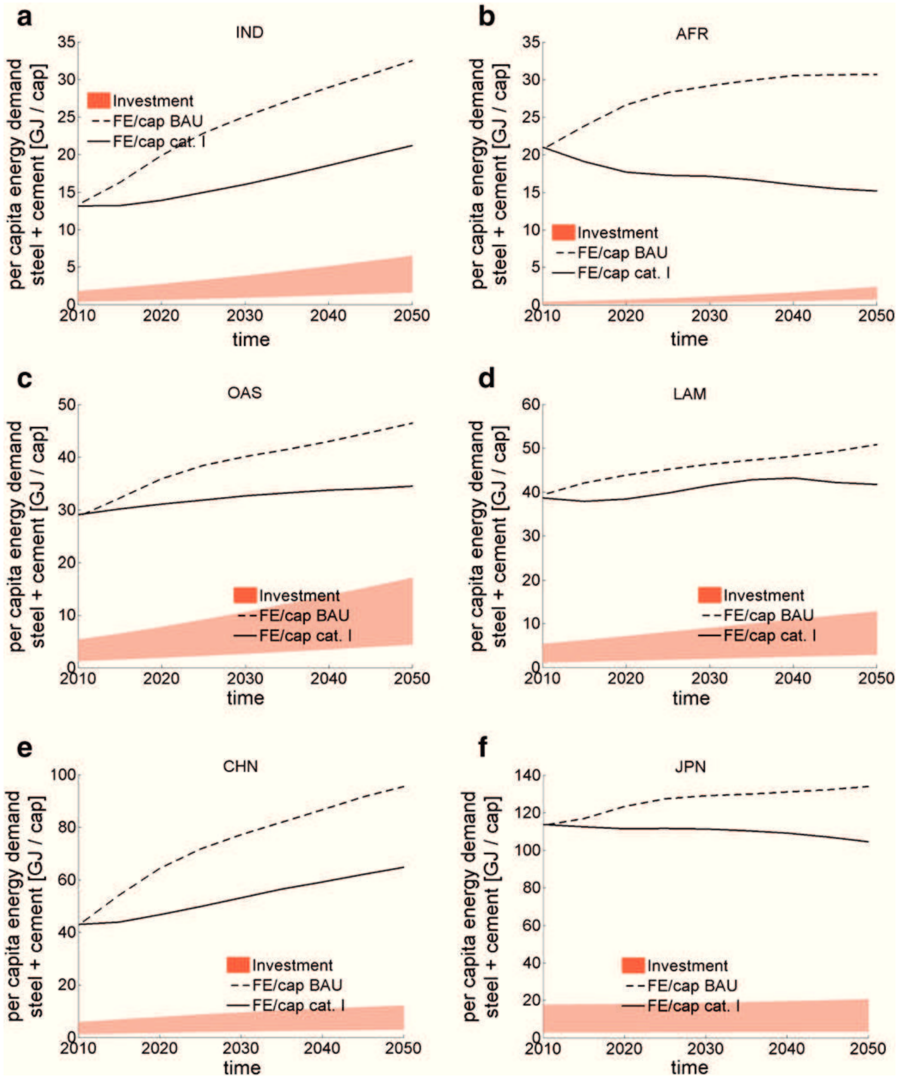

Fig. 6. Ranges of energy demand for cement and steel production in comparison to FE demand in different mitigation scenarios as calculated by the ReMIND model. The upper bound assumes the current energy use and the lower bound the thermodynamic limit for future production of cement and steel. The projections are results from the econometric model based on capital investment and population. The black line indicates energy demand in a ReMIND policy scenario (cat I), while the dashed line indicates energy demand in a ReMIND BAU scenario. Regional aggregation follows the regions represented in the ReMIND model. Please note different scales.

production techniques. While for developed countries and China, the energy needed for the supply of infrastructure accounts for only a small part of the overall energy supply, it makes up a significant share for India (a), OAS (c), and LAM (d). For Sub-Saharan Africa (b), we calculate lower levels of per capita energy for steel and cement in 2050, however increasing and converging toward developed country levels with increasing levels of GDP. In any case, economic development is expected to go hand in hand with additional energy use for infrastructure. For developed countries (here exemplarily shown for Japan, Fig. 5f) we find that future energy demand for cement and steel ranges between 2 and 20 GJ per capita in the year 2050, depending on the energy intensity levels of the future and thus remaining roughly at today's levels.

In summary, we can conclude that additional energy will be needed in the future for the construction of infrastructure in developing countries. The magnitude of infrastructure energy needs will depend on the rate of technological progress, but – at least in the short to medium term – will likely be of similar magnitude as, and in addition to, the level of final energy that appears necessary for fulfilling basic household needs, i.e. approximately 10 GJ per capita. As discussed in our analysis of IAM outputs, and particularly for developing countries and regions such as India, Sub-Saharan Africa, other parts of Asia (OAS) and Latin America total available final energy of 20 GJ per capita is projected. This quantity of energy would hence roughly be in line with what will be needed to fulfill basic needs on the household level and for steel and cement production, but would not leave energy available neither for consumption beyond the subsistence level nor other infrastructure needs. Energy for transportation infrastructure (e.g. bitumen) as well as other metals like copper or aluminum would add to the numbers presented above. This puts into question the consistency of scenario results that foresee substantial economic growth in developing regions, while final energy per capita levels stagnate at today's levels or even decrease.

5. Implications for Climate Policy

Globally, human-kind is faced by the twin challenges of mitigating climate change and overcoming poverty. Despite the urgency of solving the climate problem, mitigation policy should not trap developing countries in a state of poverty. At the same time future development processes should avoid technological lock-ins, e.g. in carbon-intensive infrastructures or energy systems.

When looking at low-stabilization scenarios produced by IAMs, here shown mainly using the ReMIND-R model but recognizing that other models give qualitatively similar results (see Appendix B for a comparison of ReMIND-R results with other IAMs), we find that historical correlations between economic growth and energy use are discontinued in mitigation scenarios, both with respect to a postulated (and observed) energy threshold as well as with respect to increasing energy use in the course of development. In model results for mitigation scenarios, final energy demand in developing regions (AFR, LAM) stays approximately at current (low) levels, whereas per capita GDP rises significantly. At the same time, developing countries are projected to face higher energy intensity improvements than developed countries. At first sight, the model results seem to be either not realistic or driven by very strong implicit assumptions.

To understand the plausibility of model results, the most important question is whether developing countries will be able to decouple their growth from energy use and – looking at the differences between BAU and policy scenarios – how fast this can be achieved. We are rather pessimistic that it is possible for low income countries to develop without increasing their level of energy use, given the indicated need for energy to drive GDP growth. In addition to energy required to satisfy basic needs at the household level, energy is also embedded in the construction of infrastructure when affluence levels go beyond the satisfaction of basic needs. All countries that have reached higher development levels in the past have increasingly used energy-intensive inputs like steel and cement and it is hardly plausible that this correlation will break, at least in the near future.[20] This impression is confirmed by an analysis of the current developing process in India or China (Steckel et al., 2011). Recent results from the literature (Jakob et al., 2012b) also imply that historical patterns of energy use are repeated for developing countries and leapfrogging in this respect will be hard to achieve if capital accumulation will remain an important driver of economic growth in the future. However, assuming that scenario results are robust, we can provide a twofold interpretation:

> First, only with massive improvements of energy intensity will it be possible to dramatically reduce the energy used for capital accumulation as compared to patterns observed in the past. This result highlights the urgent need for drastic efficiency improvements and the simultaneous provision of latest technologies to developing countries. Our results imply that bringing production processes of infrastructure inputs toward their thermodynamic limits might allow scenario results for developing countries to be achievable in reality. However, considering historic trends, no dramatic improvements in the efficiency of these processes can be expected in the near-term. Thus, the efficiency gains implicitly assumed by the models seem to be out of reach. Alternatively a total or partial replacement of energy-intensive inputs by low energy alternatives is theoretically conceivable, e.g. by newly developed materials or methods; however, this option requires a significant leap of faith.
>
> The second interpretation is that developing countries might reach high levels of economic development without accumulating energy-intensive capital. Of course, for our analysis focusing on infrastructure it is also conceivable that necessary inputs are imported; however, as both steel and cement are not easy to transport, importing these inputs over large, trans-regional distances seems to be rather unlikely and would be unprecedented in the past. Also, it is not indicative from scenario results that energy for steel and cement is provided in other regions. In principle it is possible to imagine societies whose economic growth is not based on capital accumulation, thinking of a service-oriented society.

Both interpretations imply strong underlying assumptions. Some of the results are based on the ReMIND-R model, which does not explicitly represent the energy needs for the infrastructure build-up during the development process, nor includes any explicit energy access targets for development. We have shown that the general tendency of very low levels of final energy per capita consumption is robust over a whole set of different models. Our results point to the need to spell out the details of energy demand structures more explicitly, in particular for the developing world. Analyzing energy needs at different stages of development is a promising future area of research that is in its infancy in the IAM community (Daioglou et al., 2012; Krey et al., 2012). A possible outcome of calibrating IAMs to such bottom-up derivations of energy demand could be that current mitigation scenarios are too optimistic with respect to energy consumption in developing countries. Such a finding could challenge one of the most important conclusions derived by IAMs, namely that mitigation costs can be expected to be comparatively modest. In general, this analysis raises the question whether a stronger differentiation between developed and developing countries is necessary in IAMs. For example, IA modelers could represent energy access policy targets in terms of a minimal energy input level that should be achieved to guarantee reasonable development levels. As of today, these questions – along with other important issues of sustainability – are not taken into account in most IAM analyses.

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Appendix A. Summary Statistics

Table A1
Summary statistics for developing countries.

DC	Observations	Mean	Std. dev.	Min	Max
ln steel	156	9.592039	1.785397	5.370638	12.83397
ln cement	156	8.568707	1.09147	6.363028	11.21321
ln *GDP*	156	−.1455549	.6935545	−1.414846	1.046656
ln *INV*	156	−1.79617	1.002467	−3.773844	−.1269643
ln *POP*	156	13.36882	.392945	12.68064	14.10544

Table A2
Summary statistics for OECD countries.

OECD	Observations	Mean	Std. dev.	Min	Max
ln steel	78	11.66662	.2948216	11.12219	12.2184
ln cement	78	8.940087	.5110286	8.286269	9.778831
ln *GDP*	78	1.87636	.492687	.6317062	2.617282
ln *INV*	78	.6208335	.4117358	−.3879909	1.325895
ln *POP*	78	12.42075	.5565926	11.66828	13.10009

[20] One could even argue that climate change impacts will increase the demand for cement, due to increased corrosive damages at existing infrastructure (Stewart et al., 2011).

Table A3
Parameters from the econometric model including country-specific fixed effects.

	Coef.	Std. err.	*t*	*P* > |*t*|	[95% conf. interval]
Cement_GDP					
DC					
β	.7431696	.0586947 |	12.66	0.000	.6271817 .8591575
γ	1.899377	.1173259	16.19	0.000	1.667527 2.131228
α_{MENA}	−16.19797	1.517162	−10.68	0.000	−19.19607 −13.19988
α_{CHN}	−16.67259	1.637676	−10.18	0.000	−19.90884 −13.43635
α_{IND}	−17.16932	1.626985	−10.55	0.000	−20.38444 −13.9542
α_{AFR}	−17.36198	1.57274	−11.04	0.000	−20.46991 −14.25406
α_{LAM}	−16.42157	1.513404	−10.85	0.000	−19.41224 −13.43089
α_{OAS}	−16.4699	1.571013	−10.48	0.000	−19.57441 −13.36538
Cement_INV					
DC					
β	.5523936	.0438784	12.59	0.000	.4656845 .6391026
γ	2.019974	.1137714	17.75	0.000	1.795147 2.2448
α_{MENA}	−16.8022	1.502156	−11.19	0.000	−19.77064 −13.83375
α_{CHN}	−17.61418	1.61167	−10.93	0.000	−20.79903 −14.42932
α_{IND}	−17.95363	1.604435	−11.19	0.000	−21.12419 −14.78307
α_{AFR}	−17.88295	1.558922	−11.47	0.000	−20.96358 −14.80233
α_{LAM}	−16.95098	1.501101	−11.29	0.000	−19.91734 −13.98462
α_{OAS}	−17.45866	1.542884	−11.32	0.000	−20.50759 −14.40973
Steel_GDP					
DC					
β|	.7518711	.1359855	5.53	0.000	.483147 1.020595
γ	1.448846	.271824	5.33	0.000	.9116889 1.986004
α_{MENA}	−10.18157	3.515003	−2.90	0.004	−17.12765 −3.235493
α_{CHN}	−8.918611	3.794213	−2.35	0.020	−16.41644 −1.420782
α_{IND}	−9.415145	3.769444	−2.50	0.014	−16.86403 −1.966262
α_{AFR}	−11.91986	3.643768	−3.27	0.001	−19.12039 −4.719323
α_{LAM}	−8.655937	3.506297	−2.47	0.015	−15.58481 −1.727064
α_{OAS}	−8.91623	3.639768	−2.45	0.015	−16.10886 −1.723602
Steel_INV					
DC					
β|	.4643985	.1045849	4.44	0.000	.257726 .671071
γ	1.6638	.2711759	6.14	0.000	1.127923 2.199676
α_{MENA}	−12.11991	3.580412	−3.39	0.001	−19.19524 −5.044572
α_{CHN}	−11.27925	3.841441	−2.94	0.004	−18.87041 −3.688092
α_{IND}	−11.72973	3.824196	−3.07	0.003	−19.28681 −4.172646
α_{AFR}	−13.99472	3.715715	−3.77	0.000	−21.33743 −6.652015
α_{LAM}	−10.50539	3.577898	−2.94	0.004	−17.57576 −3.435026
α_{OAS}	−11.27217	3.677489	−3.07	0.003	−18.53934 −4.005
Cement_GDP					
OECD					
β	−.0644126	.0456507	−1.41	0.162	−.1553943 .026569
γ	1.521589	.2739977	5.55	0.000	.9755122 2.067665
α_{EUR}	−10.10795	3.510918	−2.88	0.005	−17.10519 −3.110696
α_{USA}	−10.25885	3.34626	−3.07	0.003	−16.92794 −3.589763
α_{JPN}	−9.148183	3.169163	−2.89	0.005	−15.46432 −2.832051
Cement_INV					
OECD					
β	.005888	.0433015	0.14	0.892	−.0804119 .0921878
γ	1.212466	.2957029	4.10	0.000	.6231307 1.801801
α_{EUR}	−6.212061	3.838023	−1.62	0.110	−13.86123 1.437109
α_{USA}	−6.546408	3.66286	−1.79	0.078	−13.84648 .7536607
α_{JPN}	−5.611443	3.456714	−1.62	0.109	−12.50066 1.277777
Steel_GDP					
OECD					
β	.096907	.0463981	2.09	0.040	.0044358 .1893782
γ	.3927311	.2784835	1.41	0.163	−.1622857 .947748
α_{EUR}	6.704957	3.568399	1.88	0.064	−.4068511 13.81676
α_{USA}	6.303197	3.401045	1.85	0.068	−.475076 13.08147
α_{JPN}	6.812166	3.221048	2.11	0.038	.3926273 13.23171
Steel_INV					
OECD					
β	.1090002	.0428477	2.54	0.013	.0236049 .1943955
γ	.2468864	.2926035	0.84	0.402	−.3362715 .8300444
α_{EUR}	8.730784	3.797795	2.30	0.024	1.16179 16.29978
α_{USA}	8.250037	3.624467	2.28	0.026	1.026485 15.47359
α_{JPN}	8.616486	3.420482	2.52	0.014	1.799476 15.4335

Appendix B. Sensitivity Analysis of ReMIND-R Results

To test whether ReMIND-R results are model-specific we also look at qualitative results from other integrated assessment models. In the figure scenarios from the analysis shown in Fig. 4 (Section 3.1) are compared to results from the model comparison projects ADAM (Edenhofer et al., 2010) and RECIPE (Luderer et al., 2012a) (see also Section 3.1). The BAU scenario is shown in red, the category 3 stabilization scenario is indicated in black, category 2 stabilization scenario is shown in blue and the category 1 stabilization scenario is shown in green. All other scenarios are shown by gray dots, of which squares indicate baseline scenarios, circles indicate category 3 and 4 scenarios and diamonds indicate category 1 and 2 scenarios.

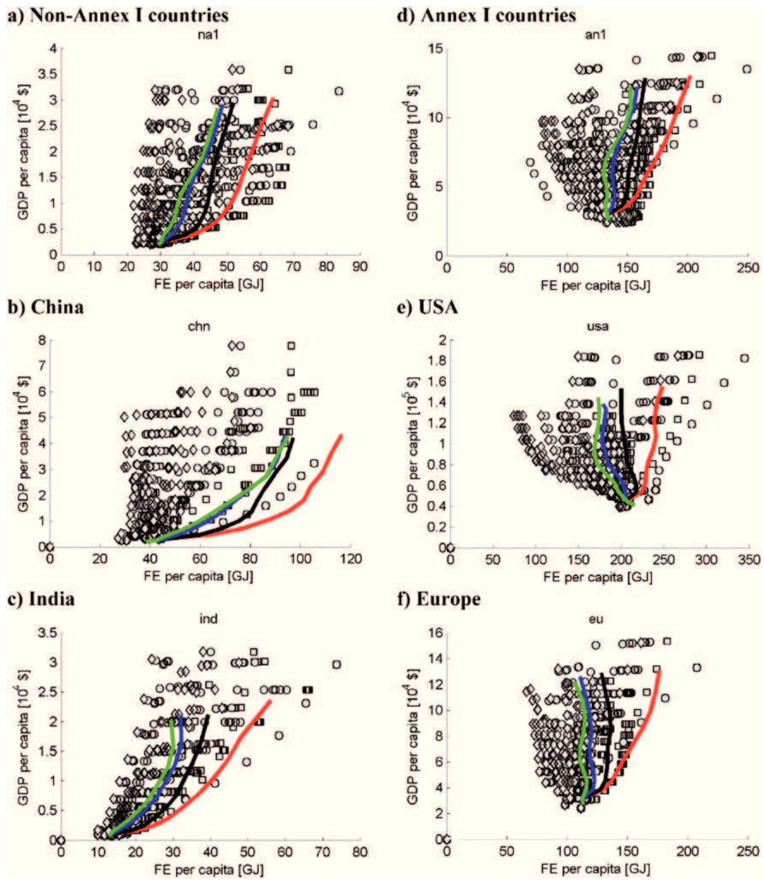

Fig. B1. Comparison of ReMIND-R results with those of other models from the RECIPE and ADAM model comparison projects. Baseline scenarios are shown by squares, category 3 & 4 scenarios by circles and category 1 & 2 scenarios by diamonds. Different colors show differently ambitious ReMIND-R scenarios, i.e. baseline (red), category 3 (black), category 2 (blue) and category 1 (green) stabilization scenarios.

We find that ReMIND-R does not produce qualitatively different results than other models that participated in both model inter-comparison projects. Obviously other models also find that in stabilization scenarios the correlation between energy consumption and economic growth is broken to an extent that might have implications for future development.

Appendix C. Cement Production in the Past

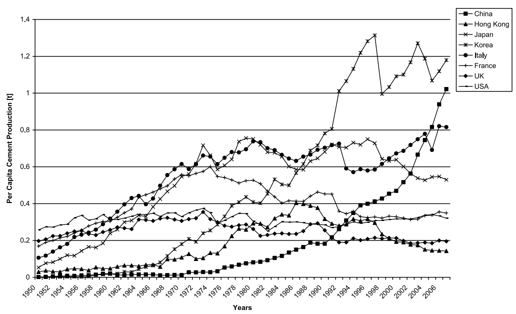

Fig. C1. Cement production per capita in selected developed countries and China from 1950 to 2008. Data are based on Boden et al. (2011) for cement and Heston et al. (2009) for population.

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Chapter 4

Economic impacts of greenhouse gas emission metrics*

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Economic impacts of alternative greenhouse gas emission metrics: a model-based assessment

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Abstract In this paper we study the impact of alternative metrics on short- and long-term multi-gas emission reduction strategies and the associated global and regional economic costs and emissions budgets. We compare global warming potentials with three different time horizons (20, 100, 500 years), global temperature change potential and global cost potentials with and without temperature overshoot. We find that the choice of metric has a relatively small impact on the CO_2 budget compatible with the 2° target and therefore on global costs. However it substantially influences mid-term emission levels of CH_4, which may either rise or decline in the next decades as compared to today's levels. Though CO_2 budgets are not affected much, we find changes in CO_2 prices which substantially affect regional costs. Lower CO_2 prices lead to more fossil fuel use and therefore higher resource prices on the global market. This increases profits of fossil-fuel exporters. Due to the different weights of non-CO_2 emissions associated with different metrics, there are large differences in nominal CO_2 equivalent budgets, which do not necessarily imply large differences in the budgets of the single gases. This may induce large shifts in emission permit trade, especially in regions where agriculture with its high associated CH_4 emissions plays an important role. Furthermore it makes it important to determine CO_2 equivalence budgets with respect to the chosen metric. Our results suggest that for limiting warming to 2 °C in 2100, the currently used GWP100 performs well in terms of global mitigation costs despite its conceptual simplicity.

1 Introduction

Effective mitigation strategies need to take different greenhouse gases (GHG) into account, such as CO_2, N_2O and CH_4. These gases have different warming effects per kilogram as well as different lifetimes in the atmosphere. A multi-gas framework establishing exchange ratios between different gases is therefore crucial. The Kyoto protocol chose the 100-year global warming potentials (GWP) as a metric to convert CH_4, N_2O and fluorinated gases (F-gases) into CO_2 equivalents, as proposed in Lashof and Ahuja (1990) and updated in subsequent

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IPCC assessments (latest values can be found in Myhre et al. (2013)) and introduced a cap on total emissions. This method reduces mitigation costs by establishing flexibility in the reduction of different GHGs ("what"-flexibility). The EMF21 study compared multi-gas to CO_2-only strategies and found substantial cost reductions for the same radiative forcing target if a multi-gas strategy was adopted (Weyant et al. 2006), see also van Vuuren et al. (2006).

Alternative metrics can be classified in terms of their climate impact proxies (e.g. temperature, forcing or economic damage), which in turn reflect underlying assumptions and implicit value judgments (Deuber et al. 2013). The global damage potential (GDP) (Kandlikar 1996) evaluates the discounted economic damages. Tol et al. (2012) showed that GWP, global temperature change potential (GTP) and global cost potential (GCP) can be considered special cases of the GDP. The GWP compares the time-integrated radiative forcing of a given substance to a reference gas, usually CO_2, over a given time horizon. This method has been challenged on economic and physical grounds (Schmalensee 1993; O'Neill 2000; Manne and Richels 2001; Fuglestvedt et al. 2003; Shine et al. 2005). A variety of alternative metric approaches were proposed. A metric that uses global temperature change at a specific point in time in the future instead of integrated radiative forcing is the GTP proposed by Shine (2005; 2007; Fuglestvedt et al. 2010). Given a climate target, integrated energy-economy-climate models can be used to derive cost-optimal emission pathways, with exchange rates of CO_2, CH_4 and N_2O emerging endogenously as the ratios of shadow prices (Manne and Richels 2001). This ratio of shadow prices is often referred to as GCP (e.g. (Johansson 2012)). However, an inter-temporal energy-economy climate modeling framework is required to derive GCPs, and their numerical value may depend on many assumptions inherent to the model.

Emissions of a specific gas are less important for reaching a given climate target when the time until the target gets binding is longer than the lifetime of the gas in the atmosphere. Time-dependent metrics capture this effect and may therefore lead to lower economic costs. Current GHG accounting systems, however, rely on constant GWP values from the IPCC second assessment report (SAR[1]), on the grounds of easier implementation. The conceptual merits and disadvantages of alternative metrics are fiercely discussed not only in the scientific community, but also in the policy arena (UNFCCC 2012). However, only few studies have quantified the implications of alternative metrics on mitigation pathways and costs. O'Neill (2003) compared 100-year GWPs to GCPs using a relatively simple model. He found global costs to be 2 % higher for GWPs and asked for more thorough analyses. Aaheim et al. (2006) confirmed their findings. Johansson et al. (2006) compared 100-year GWPs to GCPs under a 2° stabilization target. They found GWPs to be 3.8 % more expensive, which was a rather robust result confirmed with a Monte-Carlo analysis. They used exogenous baseline emission scenarios with quadratic CO_2 marginal abatement cost (MAC) curves. Reisinger et al. (2012) compared 100-year GWPs to GTPs and also explored the impact of different assumptions on MAC curves particularly in the agricultural sector. As Johansson et al., they found the impact of metrics on global costs to be in the range of a few percent. Brennan and Zaitchik (2013) investigated how different metrics influence sectoral mitigation patterns under a 5.7 Wm^{-2} radiative forcing target. They find primarily trade-offs between CO_2 and CH_4, resulting in sectoral shifts of mitigation patterns. Metrics leading to higher CH4 abatement levels favored mitigation efforts in agriculture and waste management. Ekholm et al. (2013) compared the cost increase from a cost-efficient case to a scenario with GWP100, GTP100, GTP40 and dynamic GTP under a 2° warming limit with and without rate-of-change constraint and a stochastic case. They found the dynamic GTP to lead to the least rise in costs, except in the scenario with rate-of-change constraint.

[1] GWPs have been continuously updated in the assessment reports due to changes in indirect forcing and because of changes in atmospheric composition.

While these studies addressed the dependence of aggregate global costs on the choice of metric, the question of regional cost shifts due to alternative metrics remains open. Smith et al. (2012) analyzed regional implications of different constant metrics which are roughly of the order of GWP20, GWP100, and GWP500. On a global level they find relatively small changes. On a regional level they find a larger sensitivity on the methane index in regions with a higher fraction of emissions from fossil fuel production, as they have a high mitigation potential. The focus of this article is to analyze the sensitivity of global and regional economic impacts of climate change mitigation to the choice of emission metric. We compare six 2 °C scenarios using different types of metrics. In section 3.1 we analyze the resulting exchange ratios. The impact of these exchange ratios on emission trajectories and therefore medium term targets is discussed in section 3.2. In section 3.3 we analyze the impacts of metrics on the nominal greenhouse gas emission budget. In section 3.4 we compare the global cumulated discounted mitigation costs in the different scenarios. Section 3.5 focuses on sectoral burden shifts. In section 3.6 we analyze the impact of alternative metrics on regional mitigation costs.

2 Methods

2.1 The REMIND model

For our analysis, we use the multi-regional integrated assessment model REMIND (Bauer et al. 2012; Leimbach et al. 2010; Luderer, Pietzcker et al. 2012a). It is a hybrid energy-economy model with a hard-coupled reduced-complexity climate model.

The world is divided into 11 regions. Each single region is modeled as a hybrid energy-economy system and is able to interact with the other regions by means of trade. Tradable goods are the exhaustible primary energy carriers coal, oil, gas and uranium, the composite good, and emission permits.

The economy sector is modeled by a Ramsey-type growth model which maximizes the utility, a function of consumption. Labor, capital and end-use energy generate the macroeconomic output, i.e. GDP. The produced GDP covers the costs of the energy system, the macroeconomic investments, the export of the composite good and consumption.

The energy sector is described with high technological detail. It uses exhaustible and renewable primary energy carriers and converts them to final energies as electricity, heat and fuels. Various conversion technologies are available, including technologies with carbon capture and storage (CCS). Emission factors for CO_2, SO_2, and black and organic carbon are assigned on a technology level to calculate emissions arising from the energy system. CH_4 and N_2O emissions from the energy system are calculated on a technology level as well. Emissions from agriculture are taken from the model of agricultural production and its impact on the environment (MAgPIE) (Lotze-Campen et al. 2008) and have abatement options prescribed via marginal abatement cost curves (Lucas et al. 2007). CH_4 and N_2O emissions from waste are calculated based on GDP and population development. Other emission sources like open burning are prescribed exogenously. A more detailed description of emission modeling can be found in the supplementary material S2.

A reduced-form climate model is hard-coupled to the energy-economy model. The use of the simplified climate model within the optimization allows us to derive model-endogenous, economically optimal, time-variant exchange ratios given an exogenous constraint on man-made radiative forcing or temperature change. A detailed documentation of the REMIND model is provided in Luderer et al. (2013).

The use of the MAGICC6 model (Meinshausen et al. 2011) in a post-processsing mode allows us to describe climate outcomes in greater detail. A description of the simple climate model and a comparison between this model and MAGICC6 for the most important climate variables can be found in the supplementary material S4.

2.2 Scenario description

We compare six alternative metrics, three fixed and three time-dependent. The fixed metrics are GWPs with three different time horizons 20, 100 and 500 years, denoted as GWP20, GWP100 and GWP500, respectively. Values of the GWPs are taken from the fifth assessment report of the IPCC (Myhre et al. 2013) with the exception of GWP500, which was not updated and is therefore taken from the fourth assessment report (Forster et al. 2007). The GTP is time-dependent, yet exogenous. We calculated it numerically using our simplified climate module, which also determines GCP values. In each time step, the absolute GTP for each gas is given as the change in temperature in 2100 induced by an additional pulse emission of the specific gas in that time step. The GTP is then defined as the ratio of absolute GTP of a specific gas to the absolute GTP of CO_2 (Shine et al. 2005). The remaining two metrics are GCPs, which are time-dependent and emerge endogenous from the model. To ensure comparability across the experiments with alternative metrics, we chose the climate policy constraint such that the increase in 2100 global mean surface temperature is limited to 2 °C relative to pre-industrial levels. There is a fundamental difference between scenarios in which exchange ratios are calculated endogenously by the model, and scenarios in which we use exogenously set exchange ratios. In the former we set a climate target on the temperature in 2100 and run scenarios with an overshoot (GCPov) as well as a not-to-exceed temperature target (GCPnte). When exchange ratios are set exogenously, the climate module is not needed in the optimization routine. In that case, a GHG emissions budget is calculated by converting CH_4 and N_2O emissions into CO_2 equivalents using the specific metrics and summing over the time horizon 2005–2100. In an iterative procedure, the sum of CO_2 equivalents is limited such that the 2° target in 2100 is met, with overshooting before allowed. The six climate policy scenarios are summarized in Table 1. In addition, we run a reference scenario without climate policy, which is referred to as BASE in the following.

3 Results

3.1 Exchange ratio and permit prices

The main difference between the various scenarios is the difference in the exchange ratios between CO_2 and CH_4 or N_2O, respectively (Fig. S5). The exchange ratio can be interpreted as

Table 1 Climate policy scenarios using alternative metrics. Nominal multi-gas CO_2eq budgets are different because of different CH_4 exchange ratios.

Name	Description	Target	Time-dependent	Exchange ratio
GCPov	Temperature overshoot	2° in 2100	Yes	Endogenous
GCPnte	Temperature not-to-exceed	2° not-to-exceed	Yes	Endogenous
GWP20	Multi-gas budget	3985 Gt CO_2eq	No	Exogenous
GWP100	Multi-gas budget	2852 Gt CO_2eq	No	Exogenous
GWP500	Multi-gas budget	2187 Gt CO_2eq	No	Exogenous
GTP	Multi-gas budget	2689 Gt CO_2eq	Yes	Exogenous

the ratio of shadow prices of CH_4 (Fig. S4) of N_2O and CO_2 (Manne and Richels 2001). Therefore it also defines the ratio of permit prices between different gases. It is prescribed exogenously in the GWP (constant) and GTP (time-dependent) scenarios. In the GCP scenarios, the exchange ratios between the gases emerge endogenously in the model. For N_2O, the different metrics vary little, with the exception of GWP500, which is almost 50 % lower than the others. Even time-varying metrics are nearly constant over time due to the comparable lifetimes of N_2O and CO_2. For CH_4 on the other hand, there are large variations within the different metrics as well as over time due to its shorter lifetime in the atmosphere. The fixed ratios of the GWPs already span a large range of possible variations. The time-varying metrics all start close to zero in 2020, but rise with different speeds to different final levels. The similar behavior of GTP and GCPov was already reported in Shine et al. (2007) and analyzed in Johansson (2012) and Tol et al. (2012). We observe a faster increase for the not-to-exceed target as compared to the overshoot target. In the former, the target is binding earlier. This means that abatement of shorter lived gases as CH_4 is valuable earlier, which leads to a faster rise of the GCP during the first 50 years. Our calculation of GTP will cost-effectively reach an end-point temperature without regard for peak temperature which is reached before 2100. This makes it comparable with GCPov. If it were designed to reduce peak temperature, values would rise higher earlier in time and be more similar to GCPnte (Tanaka et al. 2013).

3.2 Emissions

CO_2 emissions vary much less with metric choice than N_2O and CH_4 because they have to be reduced in any case if the 2 °C stabilization target is to be achieved (Fig. 1a). We find that

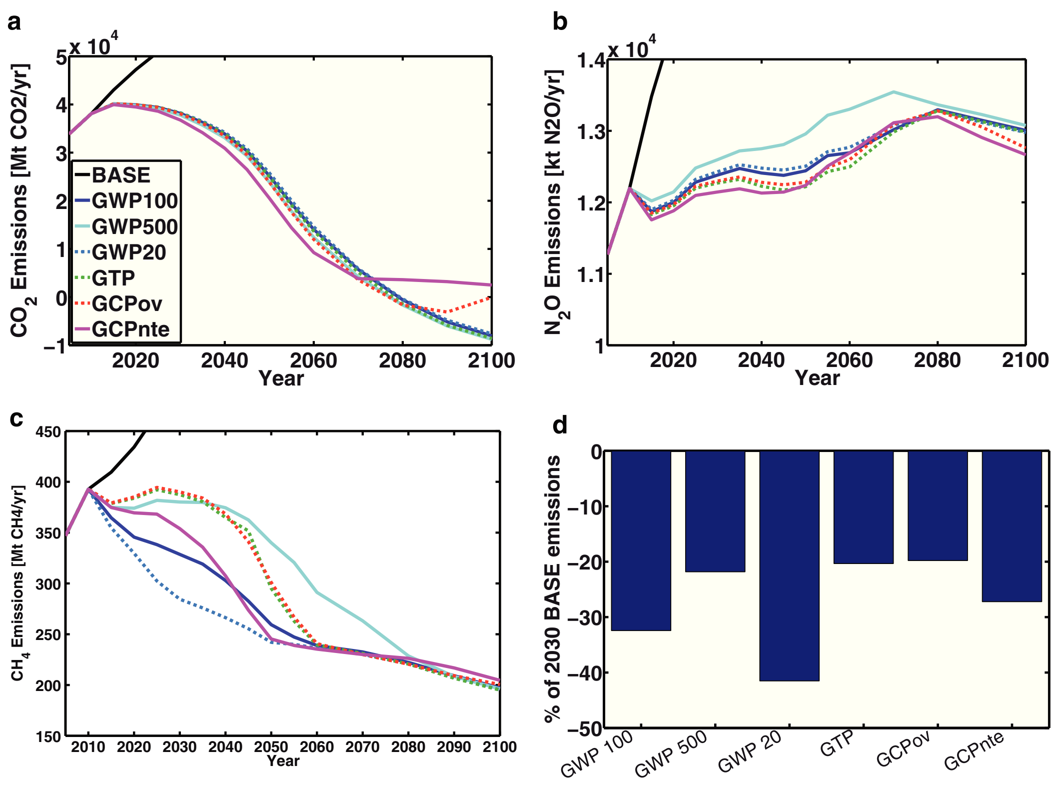

Fig. 1 Emission pathways of **a**) CO_2, **b**) N_2O and **c**) CH_4. Panel **d**) shows the relative change in global CH_4 emissions in 2030 compared to BASE in percent.

metrics with higher transient CH_4 emissions as GTP, GCPov, and GWP500 have lower CO_2 emissions almost throughout the century. The reason for this is that CH_4 abatement potentials (see supplementary material S5) are fully exhausted towards the end of the century, leading to equal CH_4 forcing for all scenarios. Even in GWP500, where CH_4 prices are lowest at the end of the century, these prices are sufficient to fully exploit the entire abatement potential. With CH_4 emissions being equal at the end of the century, it is the higher transient CH_4 emissions in case of time-varying metrics and GWP500 which contribute more to 2100 temperature rise. This higher contribution to 2100 temperature rise due to higher transient CH_4 emissions has to be compensated for by lower CO_2 emissions.

For N_2O and CH_4, the different exchange ratios translate directly to different emission pathways. The higher the exchange ratio, the higher is the value of the specific gas, and the lower are its respective emissions. For N_2O the exchange ratios are similar for all cases and almost constant over time, therefore we see little variation in the emission pathways (Fig. 1b). Only in the GWP500 scenario, where the exchange ratio is lower, are emissions slightly higher than in the other scenarios. CH_4 emissions decrease to similar levels in 2080 in all scenarios, since by then CH_4 prices are sufficiently high to exhaust the mitigation potentials represented. However, they start declining at different points in time, depending on the exchange ratio (Fig. 1c). In the GWP100 and GWP20 scenarios, where exchange rates start at a comparatively high level, CH_4 emissions start to decrease immediately. In scenarios where the exchange rate is time-dependent, we observe a peak of CH_4 emissions, with the height and timing of the peak depending on the evolution of the exchange rate. In the cost-minimizing scenario GCPov emissions start declining the latest. This means that the choice of metric regulates short-term CH_4 emission reductions. Figure 1d shows the change in CH_4 emissions in 2030 compared to baseline levels. Depending on the choice of metric, short–term CH_4 emissions reductions range from more than 40 % in the GWP20 scenario to around 20 % in the GCPov and GTP scenario.

3.3 Impacts of metric on emission budget

The choice of GHG metric has a two-fold effect on multi-gas CO_2 equivalence emissions. First, the economic incentive to abate non-CO_2 gases depends on the exchange ratio, giving rise to different physical emission fluxes. Second, the choice of metric affects the nominal CO_2-equivalences per metric ton of CH_4 or N_2O. Chiefly because of the latter effect, the optimal nominal CO_2eq budget to reach the 2 °C target depends strongly on the choice of the metric.

Cumulated CO_2 emissions show only moderate differences across scenarios. For N_2O, all chosen metrics are very similar with the exception of GWP500 (Fig. S5). This leads to comparable N_2O emissions budgets in all scenarios (Fig. S6). Only in the GWP500 scenario, where the exchange ratio is lower by about a factor of two are the emissions slightly higher than in the other scenarios. However, the lower exchange ratio still leads to lower cumulated emissions in terms of CO_2 equivalents. The exchange ratios for CH_4 show much larger variations, which are also reflected in the budgets. A higher exchange ratio leads to lower emissions in the specific scenario. In terms of CO_2 equivalents, the high exchange ratio overcompensates the lower emissions and leads to a higher nominal budget (Fig. S6). In the GWP20 scenario, where the exchange ratio for CH_4 is high from the beginning, the CH_4 budget is almost as high as the CO_2 budget. When comparing the two extreme scenarios GWP20 and GWP500, we see that GWP20 needs a budget almost twice as high to reach the same temperature target. Therefore, when choosing a multi-gas emission budget, it is extremely important to decide on the metric first.

3.4 Global costs

In the last sections we have seen that the choice of metric leads to little difference in CO_2 emissions among the scenarios. As CO_2 abatement costs dominate global costs, we expect to also see little difference in global costs. In the following we will measure global costs as the cumulated and discounted difference in consumption between climate policy and reference scenario relative to consumption. We use the discount rate internal to the model, which is about 5 % per annum. All scenarios reach the same temperature in 2100, but some may overshoot before. A lower transient temperature would be environmentally favorable, but might lead to higher costs. A similar trade-off between economic costs and temperature has been explored in Luderer et al. (2013) for a wider range of temperature target levels. For mitigation with policy stringency they found cost increases of around 0.1 % of GDP for each 0.1 °C reduction in the global temperature target in the vicinity of 2 °C. Figure 2 shows the global cumulated discounted consumption loss as a function of the maximal temperature. For most scenarios we find that higher economic costs are accompanied with lower peak temperature. Some scenarios as e.g. GWP500 have higher costs despite higher temperature, which indicates that they are less efficient. However, the variation in temperature is so small that its explanatory power is somewhat limited. Temperature peaks between 2 and 2.1 °C for all scenarios. The variation of consumption losses is between 1.07 and 1.16 %. This range is higher than found by Reisinger et al. (2012), but only due to the GCP scenarios which they had not included in their analysis.

We find that GWP100, GCPov and GTP have almost equal global costs. This is a result of a combination of climate target and CH_4 abatement options, which lead to a full exhaustion of abatement options in all scenarios. Even though CH_4 prices are higher at the end of the century in the GTP and GCPov scenarios, there are no further abatement options available. Therefore it is not possible to compensate higher CO_2 emissions early in the century by lower CH_4 emissions towards the end. This leads to all three scenarios having similar CO_2 emission trajectories. Since CO_2 emission reductions dominate the costs of abatement, global costs are similar.

In our analysis we do not take avoided costs due to health benefits into account. Scenarios as GWP20 and to a lesser extent also GWP100 lead to lower transient CH_4 emissions. Decreasing anthropogenic CH_4 emissions decrease near surface ozone concentration, which would yield positive effects on human health and crop yield. Cox and Jeffery (2010) suggest that these co-benefits may outweigh the marginal abatement costs.

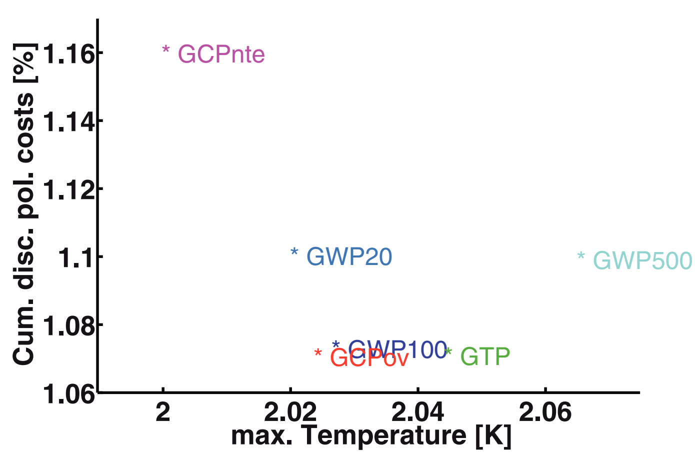

Fig. 2 Global cumulated discounted mitigation costs (measured in terms of aggregated 2005–2100 consumption losses relative to BASE consumption) vs. maximal global mean temperature change. There is a trade-off between economic cost and temperature. However scenarios like GWP500 seem to be less efficient as they achieve higher temperatures at higher costs.

3.5 Sectoral burden shift

In the last section we have seen that global costs are not much affected by the choice of metric. However there could be shifts in sectoral and regional mitigation burden which might lead to differences in the distribution of mitigation costs. To assess the sectoral mitigation burden Fig. S7a shows the sectoral distribution of cumulated emissions of CO_2, CH_4 and N_2O. We distinguish three sectors. The fossil fuels and industry (FF&I) sector comprises the energy system, industry, and transport. CH_4 emissions in the FF&I sector are fugitive emissions arising from fossil fuel extraction, processing, and transportation. Emissions in the land use/agricultural sector arise in case of CO_2 from land-use change, in case of CH_4 and N_2O from agriculture and forest and savannah burning. Thirdly we consider emissions from waste disposal and handling. For CO_2 and N_2O there is almost no difference between scenarios. Cumulated CH_4 emissions are highest in the GTP scenario and lowest in the GWP20, with GTP being about 25 % higher. All sectors contribute to the lower emissions in the GWP20 scenario. This is in line with Brennan and Zaitchik (2013), who also found larger emissions reductions in a GWP20 scenario, to which agriculture and the energy sector contributed about equal amounts. Figure S7b also shows the sectoral distribution of cumulated emissions, but this time converted into CO_2 equivalents, thus taking into account the metric-dependent weights attributed to CH_4 and N_2O. For N_2O there is almost no difference among all scenarios, due to the very similar exchange ratios. Only in GWP500 are N_2O land-use emissions measured in CO_2eq lower than in the other scenarios since the exchange ratio is lower. The exchange ratios for CH_4 vary widely among the scenarios. A high exchange ratio leads to high nominal CH_4 emissions in terms of CO_2 equivalents, even though the factual emissions may be lower. This affects mostly the agricultural sector where the largest share of CH_4 emissions arises (Fig. S7). Even though abatement costs remain almost constant in all sectors across scenarios, costs for emission permits would depend strongly on the choice of metric. Sectors with high CH_4 emissions as agriculture and to some extent also the use of fossil fuels are affected most.

3.6 Regional costs

As we have seen, global costs are almost independent of metrics under the assumption of perfectly efficient and fluid global markets. However, mitigation costs at a regional level generally can differ substantially from global costs (Luderer et al. 2012b; Tavoni et al. 2014), and are particularly sensitive to emissions pricing. The following analysis shows that also the choice of metric may have a significant impact on the regional incidence of mitigation costs. These effects are mainly due to four factors: non-CO_2 abatement costs, CO_2 abatement costs, energy trade, and financial transfers induced by emissions trading. Trade in agricultural goods is not considered, since this sector is not modeled explicitly. We apply a decomposition method (Aboumahboub et al. 2013) to disentangle these factors. We concentrate on shifts in regional costs induced by the use of alternative metrics. Therefore we compare all metrics to the currently most widely used GWP100. This is shown in Fig. 3. Total regional costs compared to the BASE scenario can be found in Figure S9.

First we consider non-CO_2 abatement costs. They make up only a small part of global mitigation costs, yet they can be more important on a regional level. The direction of shifts in regional costs resembles the shifts in global costs. If the CH_4 exchange ratio is high, non-CO_2 abatement costs are higher in all regions. This applies for the GWP20 scenario. All other metrics lead to lower non-CO_2 abatement costs (Fig. 3).

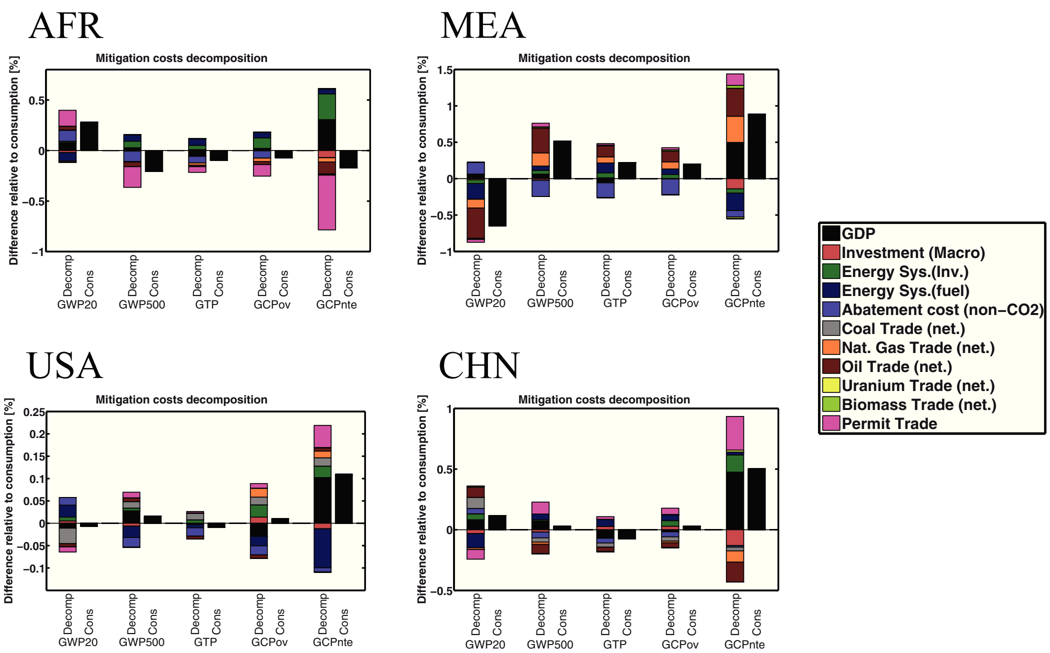

Fig. 3 Decomposition of regional mitigation costs until 2050 for selected regions. All scenarios are compared to GWP100. The black bar represents total mitigation costs as consumption loss relative to GWP100 consumption [%]. A positive value means higher costs than the reference case, a negative value means lower costs. Mitigation costs of the remaining regions can be found in Fig. S8.

In these scenarios, non-CO_2 emissions are higher, thus leaving less room for CO_2 emissions. The difference in CO_2 emission pathways is moderate, yet not negligible. It is correlated with changes in the CO_2 price pathways (Fig. S4), which, albeit small, alter the regional energy system. This already has an effect on regional mitigation costs. Another effect of different CO_2 price pathways is that they affect the third factor, energy trade. Final energy prices of fossil fuels are composed of fossil fuel resource prices and the CO_2 price, which is the dominant factor. A lower CO_2 price, as e.g. in the GWP20 scenario, decreases the final energy prices and therefore leads to a higher demand of fossil fuels. Higher CH_4 prices cannot counterbalance this trend because even at the very high CH_4 prices of the GWP20 scenario, the price of CH_4 emitted per unit oil or gas extracted is less than 20 % of the price of CO_2 emitted for the same amount, depending on the level of CH_4 abatement. A higher demand increases fossil fuel resource prices, which benefits fossil fuel producers. They will have increased revenues from trade. Fossil fuel consumers will have to pay more for their imports, but have overall benefits due to the lower emission prices. This leads to a shift in the regional incidence of climate policy costs, but has almost no effect on global mitigation costs. The losses are distributed over all fossil importers, whereas the gains are concentrated in the two most important oil and gas exporting regions, Russia (RUS) and Middle East and North Africa (MEA) (Fig. 3). These gains overcompensate additional costs for CH_4 and N_2O abatement. The complete regional breakdown in the model REMIND is shown in Table S1.

The last factor is financial transfers induced by emissions trading under a cap-and trade regime. For the present analysis, we assume a resource sharing allocation scheme with per-capita convergence similar to the one described in Tavoni et al. (2014). Under this scheme, permits are allocated according to historical emissions in 2010, and equal per capita emissions starting in 2050. Between 2010 and 2050, regional shares in global emissions are interpolated linearly. Regions with emissions below their permit allocation will therefore have additional gains from permit trade, and vice versa.

In the GWP20 scenario, CH_4 emissions are almost half of the nominal budget (Fig. S6), whereas in the GWP500 scenario they are only around 10 %. Therefore the impact of CH_4 emissions on the permit trade is much higher in the GWP20 scenario. This is disadvantageous for regions like sub-Saharan Africa (AFR), which has a very low share of CO_2 emissions but a rather high share of CH_4 emissions. In the GWP500 scenario AFR gains from permit trade due to its low CO_2 emissions and the low CH_4 exchange ratio. In the GWP20 scenario AFR has to buy permits because of the high CH_4 exchange ratio. Regions like China (CHN), Japan (JPN) and the USA, where it is the other way around, profit from the high CH_4 exchange ratio. In these regions, the high CH_4 exchange ratio results in a higher nominal budget which devalues their high CO_2 emissions.

Overall regional costs can vary in the order of 0.5 % relative to the GWP100 scenario for most metrics. Only GCPnte may lead to regional cost variations of up to 1 % relative to GWP100.

It is important to note here that the results hinge on the regional aggregation. Countries like New Zealand, which are not explicitly modeled but have a high share of agricultural emissions would likely also profit from a metric with a low relative weight on CH_4.

These results depend strongly on the exact permit allocation scheme. This implies that the choice of metric and country-specific emission sources and abatement potentials play an important role in each country's need for permits. Our results suggest that interregional wealth transfers depend on the interaction of permit allocation scheme and choice of metric. This implies that the choice of allocation scheme should be contingent on the metric to avoid inadvertent wealth transfers.

4 Summary and discussion

In this paper, we compared a range of different metrics under a climate stabilization target of 2 °C in 2100 compared to pre-industrial levels. Our study leads to the following main results:

The choice of metric determines medium term CH_4 emission levels and the global emissions budget. We found that N_2O emission trajectories are only weakly affected because the exchange ratio is rather insensitive to the choice of metric due to its lifetime in the atmosphere being similar to CO_2. CH_4 emissions are similar for all scenarios at the end of the century when the abatement potential is fully exhausted. However the point in time when abatement options are used and thus medium term emissions are substantially affected. Depending on the choice of metric, CH_4 emissions reductions in 2030 vary between 20 and 40 %. However, one has to keep in mind that the choice of metric does affect the nominal budget substantially. A high exchange ratio for CH_4 may lead to earlier emission reductions, but nevertheless increase the CH_4 budget in terms of CO_2 equivalents. When deciding on a multi-gas emission budget, it is crucial that the metric is defined first and the global budget is chosen accordingly.

Global costs are only weakly affected by alternative metrics. Due to the complete use of abatement potentials CH_4 emissions cannot be decreased further even in scenarios where prices are high. The similar CH_4 forcing at the end of the century leads to similar CO_2 trajectories in all scenarios. Therefore under the assumption of perfectly efficient and fluid global markets the choice of metric does not have much influence on the global policy costs, as they are dominated by CO_2 mitigation. Global costs of GWP20 and GWP500 are around 3.5 % and GWP100 around 1 % higher than in the cost-optimal GCPov scenario.

From this study, we find that there is a trade-off between global costs and transient climate change. Metrics with relatively high near-term CH_4 exchange ratios like GWP20 and to a lesser extent also GWP100 reduce CH_4 emissions early in time, which leads to a lower maximum temperature and a lower rate of temperature change. In return they have higher global costs. However, they have potential health benefits due to lower CH_4 burden, which leads to less tropospheric ozone. The monetary value of these benefits is neglected in our cost estimate.

Alternative metrics may lead to regional redistributions due to trade effects of fossil fuels and shifts in emissions permit trade. Changes in CO_2 emission trajectories are correlated with changes in CO_2 prices which can affect the energy system and lead to changes in regional distributions. A higher CO_2 price leads to less oil and gas consumption and therefore to lower oil and gas resource prices. Fossil fuel exporters have lower profits, while fossil fuel importers have lower fossil fuel import costs. However, due to the higher CO_2 price the cost for final energy from fossil fuel use is still higher. In addition to these shifts, distributional issues may be enhanced if one considers permit trade. In this study we considered a per capita convergence of emission allowances such that in 2050 the per capita endowment with emission permits is equal across all regions. A high CH_4 exchange rate like in the GWP20 scenario leads to a higher nominal budget. This is favorable for regions with an emphasis on CO_2, as their emission budget increases, but their nominal emissions increase only little. Regions with an emphasis on CH_4 on the other hand face a large increase in nominal emissions which outweighs the increase of their emission budget. Therefore they have to buy more permits. This is mainly the case for developing and emerging economies like Sub-Saharan Africa (AFR), India (IND) and South-East Asia (OAS). Regional cost variations are up to about 0.5 % compared to the GWP100 scenario for all scenarios except GCPnte, in which case they may go up to almost 1 % in single regions.

It would be interesting further research to analyze these effects with different allocation schemes, or incomplete sectoral coverage, e.g. by excluding agricultural emissions. Our results imply that the interplay of permit allocation and choice of metric can have a considerable influence on regional costs and benefits. National or regional emission caps should be thus contingent on the chosen metric.

The same argument holds for sectoral distributions. There is little difference in actual emissions across the different scenarios, leading to comparable mitigation costs. CH_4 intensive sectors like agriculture suffer from high CH_4 exchange ratios if permit trade is considered due to rising nominal emissions. Table 2 summarizes these results.

GWP100 performs well in terms of global costs despite its simplicity By construction, the GCPov metric is the cost minimizing choice for limiting global warming to 2 °C by 2100. However, we find that the currently used GWP100 is very close to the "efficient frontier" with only slightly higher global costs than the GCPov. These results suggest that in terms of global costs the currently used GWP100 offers a good compromise between economic efficiency and transient climate targets. It might also offer health benefits due to reduced methane concentration, which leads to reduced tropospheric ozone concentration.

It is important to keep in mind that GHG emission metrics do not only differ in terms of the emission pathways and economic costs induced, but also in terms of their institutional requirements. In contrast to the relatively simple physical metrics, economic metrics such as GCP require complex modeling tools, and depend strongly on structural and normative assumptions. Alternative metrics offer little room for gains in efficiency. However, they might

Table 2 Summary of the assessment of alternative GHG metrics with a resource sharing allocation scheme, where until 2010 all regions get the permits that correspond to their economically optimal share in global emission. Afterwards, emissions allowances decrease or increase linearly until in 2050 the per capita emission allowances are equal across all regions. Regional winners and losers are mentioned if their decrease/increase in costs is at least 0.1 % compared to the GWP100 scenario and are printed in bold if it exceeds 0.5 %.

	Transient climate change [max. T]	Global costs [% of BASE consumption]	Regional winners	Regional losers	Sectoral mitigation burden	Institutional challenges
GCPov	2.024	1.070	IND	MEA		++
GCPnte	2.000	1.160	AFR	**CHN**, LAM, **MEA**, ROW, **RUS**, USA		++
GWP20	2.020	1.100	**MEA**	AFR, CHN, **IND**, OAS	Higher abatement costs in agricultural sector	+
GWP100	2.026	1.071				o
GWP500	2.065	1.099	AFR, IND, OAS	**MEA**, RUS	Less abatement costs in agricultural sector	+
GTP	2.044	1.073	AFR, IND, OAS	MEA		+

imply differences in regional or sectoral mitigation burden. Our results suggest that a pragmatic approach would be to keep the simple but almost efficient GWP. Distributional issues can then be addressed explicitly via the choice of regional and sectoral emission caps, rather than implicitly by haggling over emission metrics.

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Economic impacts of alternative greenhouse gas emission metrics: A model-based assessment

Supplementary Material

S.1 Regional breakdown in REMIND

Model region	*Countries*
AFR	Sub-Saharan Africa w/o South Africa
CHN	China
EUR	EU27 countries
IND	India
JPN	Japan
LAM	All American countries but Canada and the US
MEA	North Africa, Middle Eastern and Arab Gulf Countries, Resource exporting countries of FSU, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states, Turkey, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

Table S1: World regions in REMIND.

S.2 Emission modeling

According to (EDGAR, 2011), the most important anthropogenic CH_4 sources are agriculture (41.6%), fugitive emissions from fossil fuel extraction and processing (31.3%), waste disposal and handling (16.8%), open burning (6.4%), and the residential sector (3.4%). For N2O the most important sources are agriculture (54.4%), industrial processes (13.5%), open burning (12.7%), energy and transportation (8.4%), indirect N2O from non-agricultural NOx and NH3 (7.1%), and waste disposal and handling (3.5%). These sources are captured in the REMIND model. We take emissions from agriculture from the model of agricultural production and its impact on the environment (MAgPIE) (Lotze-Campen et al., 2008). N_2O emissions (Bodirsky et al., 2012) directly related to bioenergy deployment are accounted for via an additional emission factor on purpose-grown bioenergy, which was also derived from MAgPIE. Emissions from open burning are assumed to remain constant at 2005 levels as reported in (EDGAR, 2011). N_2O emissions from transportation and industry are exogenous. We calculate CH_4 fugitive emissions based on the regional amount of fossil fuel extraction using region- and fuel-specific emission factors. The emission factors are derived using the emissions inventory (EDGAR, 2011) and the amount of fossil fuel extracted in each region in REMIND in 2005. Fossil fuel extraction data is taken from the international energy agency (IEA). EDGAR reports fugitive emissions in the two categories “fugitive emissions from solid fuels” and “fugitive emissions from oil and gas”. There is no further breakdown e.g. in emissions arising from extraction and emissions arising from processing or transport. We keep the category “fugitive emissions from solid fuels”, however we need to disaggregate “fugitive emissions from oil and gas” into oil and gas. To do so, we use the ratio of the sum of oil and gas emissions from the national inventory reports submitted to UNFCCC in 2009 for USA, JPN, EUR and RUS; in ROW, we use the ratio of the most important emitters with NIR data available, i.e. Australia, Canada, Turkey and Ukraine. For regions where we have no NIR data available, we use the average of the above. This yields

$$\frac{Emi_{oil}^{regi}}{Emi_{gas}^{regi}} = \frac{\sum_{NIR} Emi_{oil}^{NIR}}{\sum_{NIR} Emi_{gas}^{NIR}}. \qquad \text{(S1)}$$

From the disaggregated emissions, we calculate the emission factor for each region and fuel by dividing emissions by the amount of fossil fuel extracted. In AFR, the extracted fuel and also the emissions are so low, that emission factors cannot be calculated reliably. Small errors in measuring the emissions lead to large deviations in calculated emission factors. Therefore we use the same emission factors as for MEA. The same holds for JPN: There is so little coal extraction, that emission factors cannot be calculated reliably. Since Japan has the lowest emission factors for gas and oil, we use the minimum of the other regions for coal. Table S2 shows the emission factors we derived.

Model region	*coal*	*oil*	*gas*
AFR	19.28	1.43	23.03
CHN	14.87	1.50	31.09
EUR	10.76	1.41	12.97
IND	7.76	2.32	18.17
JPN	5.17	2.37	5.24
LAM	21.10	1.19	24.98
MEA	19.28	1.43	23.03
OAS	14.64	3.26	13.65
ROW	6.11	3.48	9.72
RUS	15.17	2.70	20.78
USA	5.17	2.57	7.70

Table S2: Emission factors for fugitive emission from coal, oil and gas in REMIND and from IPCC good practice guidelines in [Tg CH_4 / TWa].

To estimate CH_4 and N_2O emissions from waste, we use a simple econometric model. Our hypothesis is that the amount of waste per capita and thus per capita emissions are related to economic development. As a proxy for economic development we use GDP (Heston et al., 2012). We performed a panel regression between per capita emissions (E) (EDGAR, 2011) and per capita GDP (GDPc). A fixed-effects estimator is used to estimate the equation

$$\ln(E_i) = \alpha_i + \beta \ln(GDPc_i) + \varepsilon_i, \qquad \text{(S2)}$$

where α_i are country-specific parameters constant in time and the error term ε_i is assumed to be identically and independently distributed (iid). This estimate yields the parameter β, which is equal for all countries and therefore also for the aggregated regions used in REMIND. The parameters α_i are country-specific and cannot be aggregated to regions. However they simply

describe an offset and can therefore be chosen such that the regional emissions in the baseyear 2005 are correct.
In USA, EUR and JPN, CH_4 emissions from waste show a significant decline starting around 1990. In these regions, abatement measures have already been put into place. This is taken into account by using only the data from 1970 to 1990 for the regression. For the time span of our scenarios we use the emissions calculated with the linear regression as a baseline. We calculate the relative abatement for 2005 using the calculated baseline and the actual historical data. The abatement in 2005 is enforced as a minimum in the following years in all scenarios, including baseline run.
All emission types except those from open burning can be further reduced by means of a marginal abatement cost (MAC curve). In our model, abatement potentials are based on (Lucas et al., 2007), which are time- and source dependent.

S.3 Climate indicators

CO_2 and N_2O emission pathways (Figure 2) are almost the same for all scenarios. The largest differences are in CH_4 emissions which lead to slightly lower total CH_4 radiative forcing for the GWP20 scenario. Total radiative forcing peaks around 2050 at 3.2 to 3.5 W/m^2 and reaches about 3.2 W/m^2 in 2100 (Figure S1a). There is a spread in temperature of about 0.2°C in the middle of the century (Figure S1b), with GCPov leading to the highest and GCPnte leading to the lowest temperature.

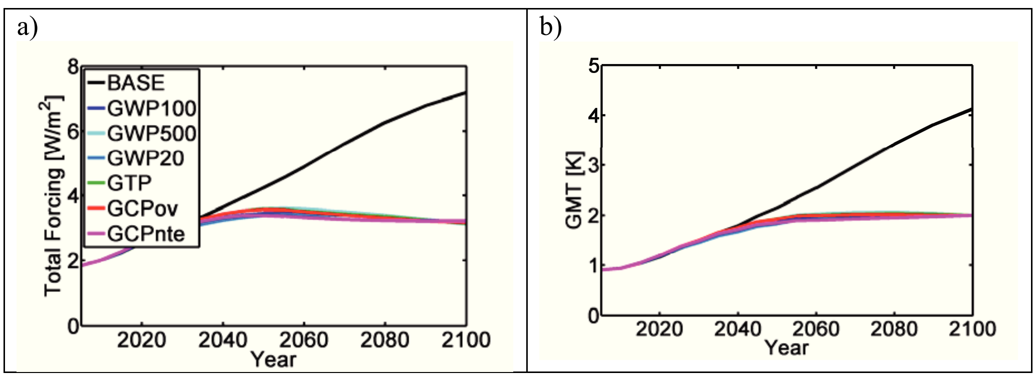


Figure S1: Total radiative forcing (a) and global mean temperature change as compared to pre-industrial times (b).

S.4 Comparison between box model and MAGICC

In the box model, the carbon-cycle is modeled as an impulse-response function with three time scales. CH_4 and N_2O radiative forcing are calculated using the IPCC third assessment report (TAR) equations (Ramaswamy et al., 2001). OH and tropospheric ozone concentrations are also using TAR equations (Ehhalt et al., 2001) SO_2, BC, and OC are included, however they are not part of the optimization routine. Direct forcing components of SO_2 and carbonaceous aerosols are calculated using a linear relation between forcing and emissions, which is calibrated to the base year 2005. Base year forcing values are taken from Forster et al. (2007). Indirect aerosol forcing is assumed to depend linearly on sulfate aerosol load of the sum of anthropogenic and natural sources (Harvey et al., 1997). All other forcing agents are exogenous. An energy balance temperature model with a fast mixed layer and a slow deep ocean temperature box calculates global mean temperature from total forcing.

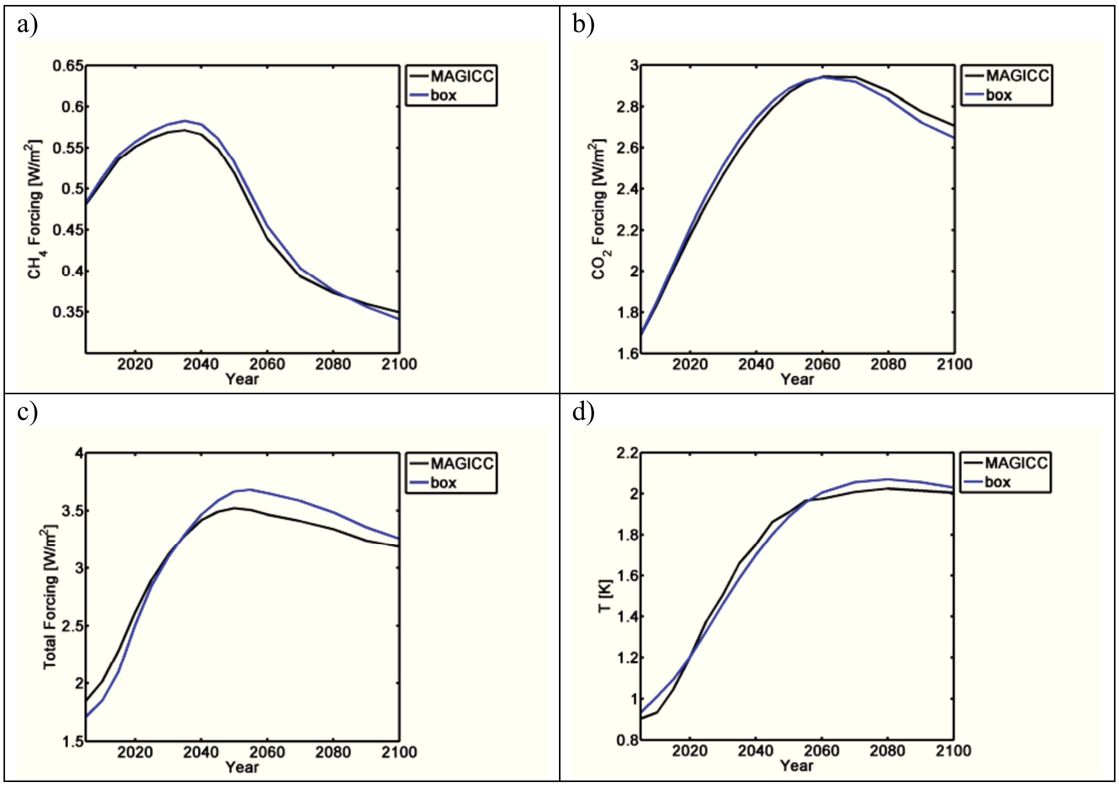


Figure S2: Comparison of a) CH_4 forcing b) CO_2 forcing c) Total forcing and d) Temperature rise between the simple box model and MAGICC6.

S.5 Abatement potentials

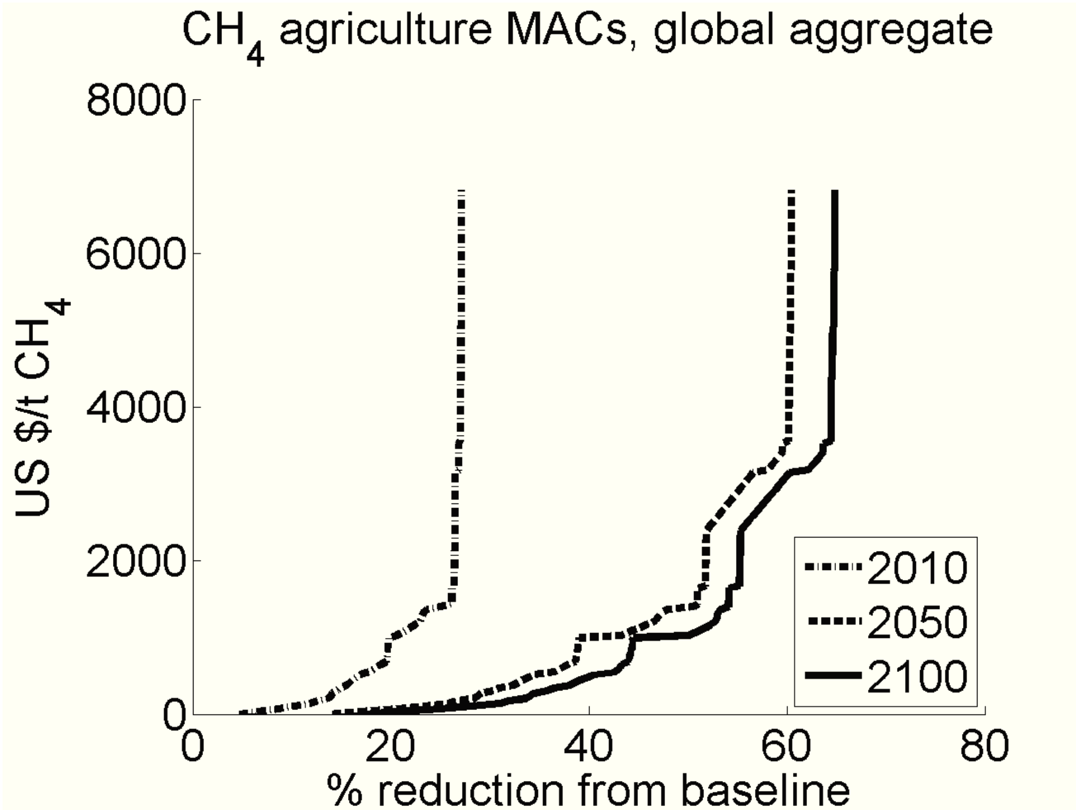


Figure S3: Globally aggregated abatement costs and potentials for CH4 from agriculture for different points in time. Marginal abatement cost curves are shifted with time such that more abatement is possible and the same level of abatement is available for a lower price. Note that 2100 CH4 prices range between roughly 10'000 $/tCH4 (GWP500) and 160'000 $/tCH4 (GTP), such that CH4 abatement potentials are fully exhausted irrespective of GHG emission metric chosen.

S.6 Additional figures

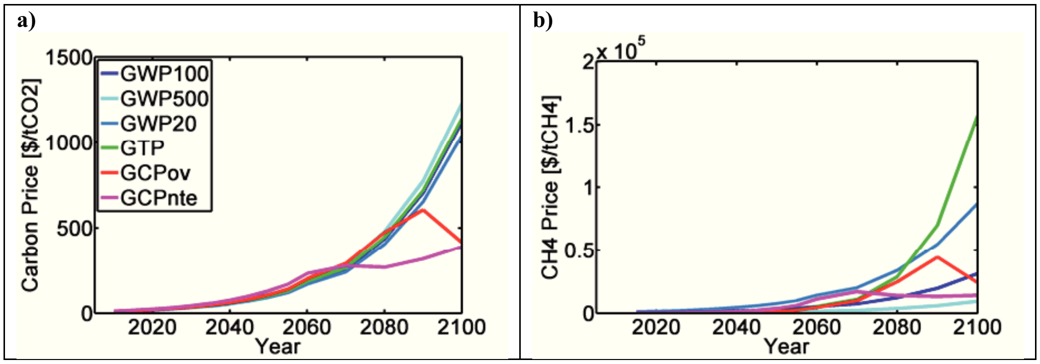


Figure S4: a) Carbon price and b) CH_4 price.

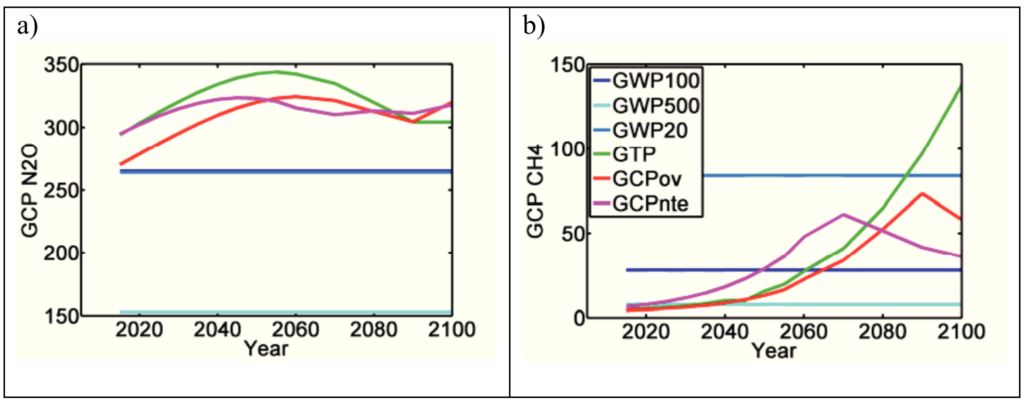


Figure S5: Exchange ratios between CO_2 and a) N_2O and b) CH_4. The exchange ratio is calculated as the ratio of shadow prices, which is prescribed exogenously for GWPs (constant) and GTP (time-dependent) and emerges endogenously in the GCP scenarios.

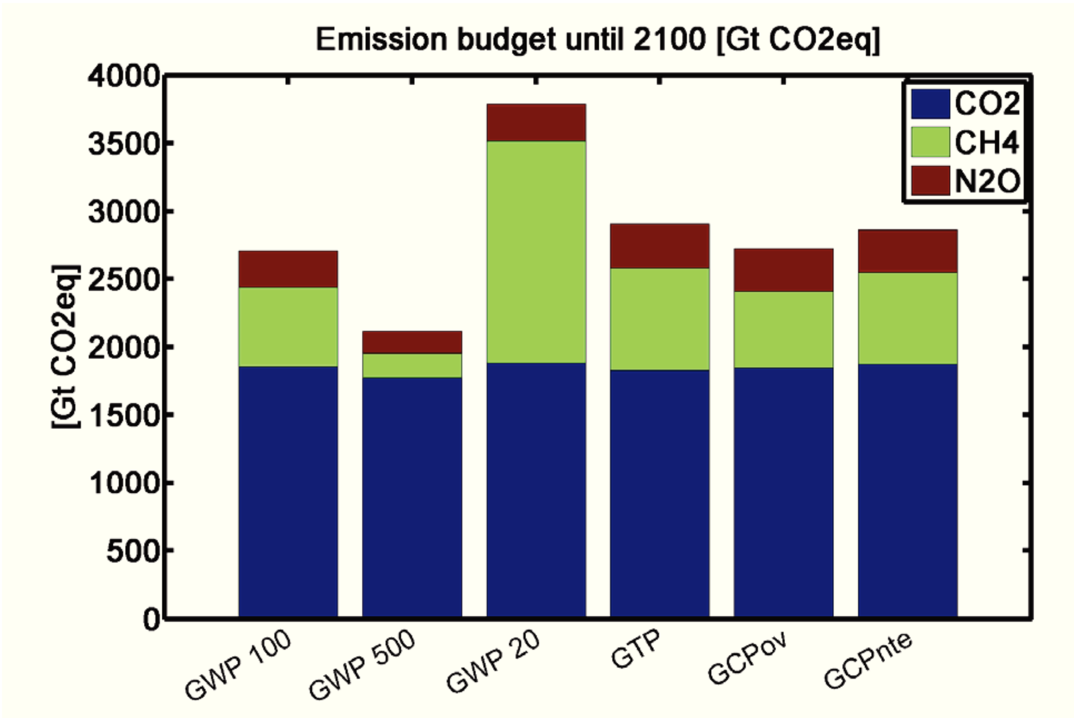


Figure S6: Emission budgets from 2005 until 2100 in Gt CO_2eq. CH_4 and N_2O emissions are converted to CO_2eq using the time- and scenario-specific conversion ratios.

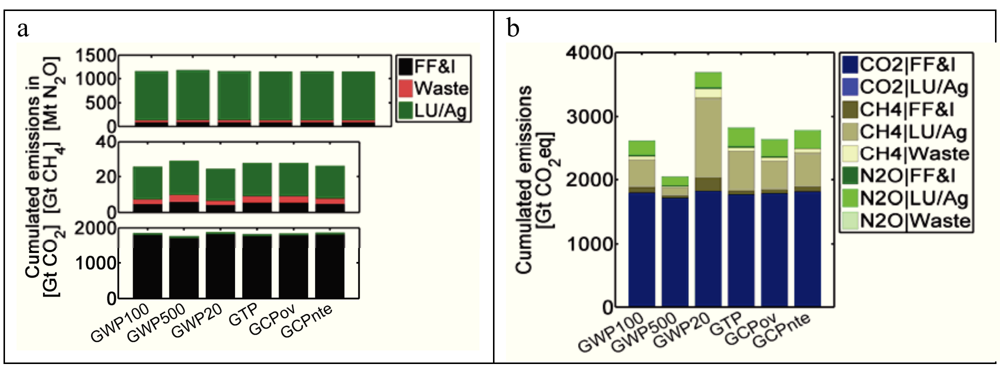
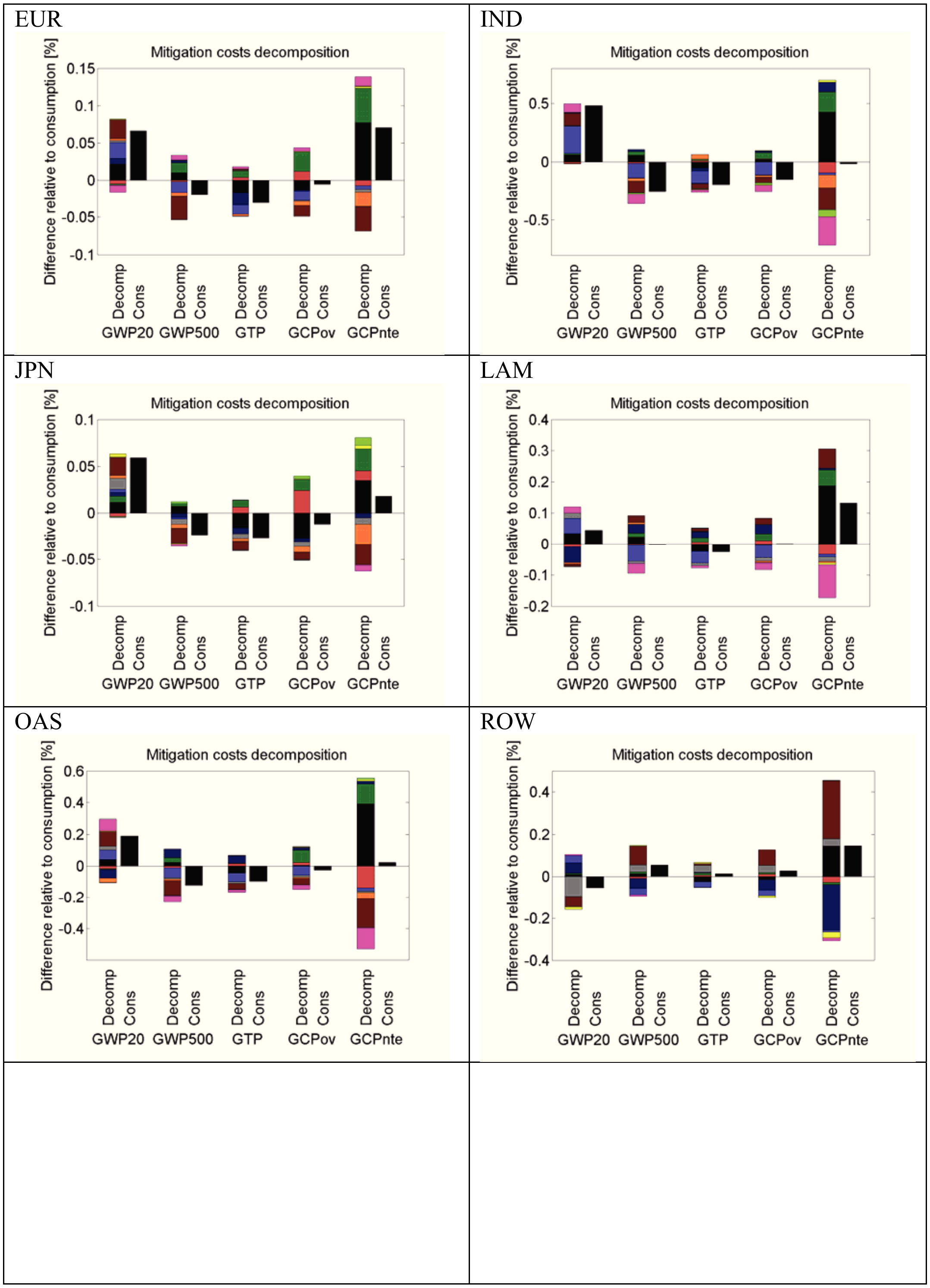


Figure S7: Sectoral allocation of cumulated emissions (2005-2100) in the climate policy scenarios for CO_2, CH_4 and N_2O. Panel a) shows cumulated emissions by sector for each gas. Panel b) shows cumulated emissions in CO_2eq, thus taking the different weights of alternative metrics into account.


EUR
Mitigation costs decomposition
Difference relative to consumption [%]
0.15 0.1 0.05 0 -0.05 -0.1
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte
IND
Mitigation costs decomposition
Difference relative to consumption [%]
0.5 0 -0.5
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte
JPN
Mitigation costs decomposition
Difference relative to consumption [%]
0.1 0.05 0 -0.05 -0.1
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte
LAM
Mitigation costs decomposition
Difference relative to consumption [%]
0.4 0.3 0.2 0.1 0 -0.1 -0.2
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte
OAS
Mitigation costs decomposition
Difference relative to consumption [%]
0.6 0.4 0.2 0 -0.2 -0.4
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte
ROW
Mitigation costs decomposition
Difference relative to consumption [%]
0.4 0.2 0 -0.2 -0.4
Decomp Cons
GWP20 GWP500 GTP GCPov GCPnte

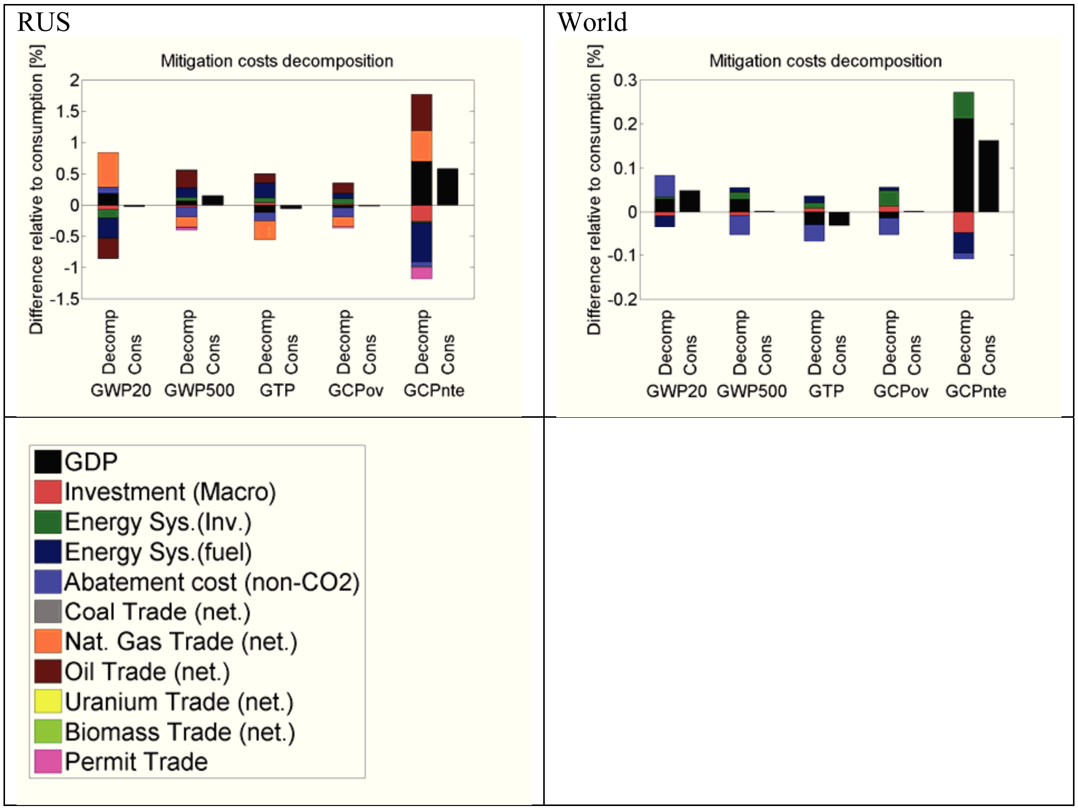
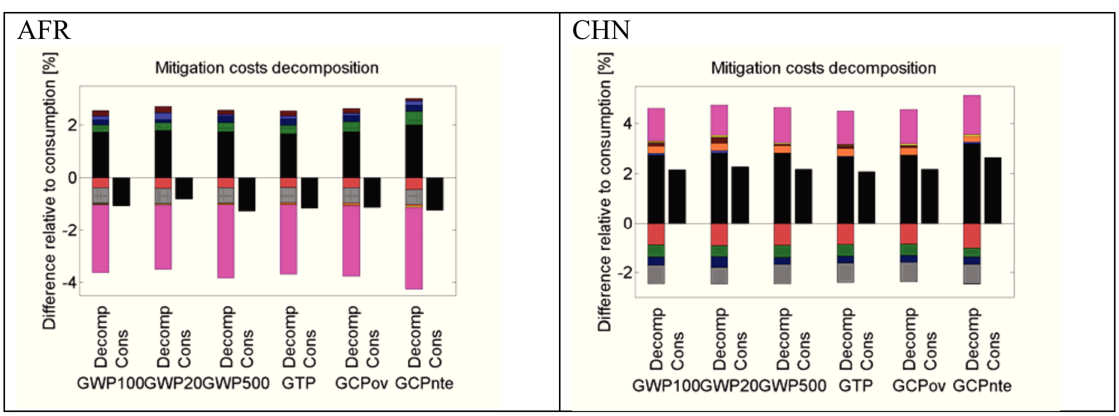


Figure S8: Decomposition of regional costs until 2050 compared to GWP100. The black bar represents total mitigation costs as consumption loss relative to GDP [%]. A positive value means higher costs than the reference case, a negative value means lower costs.



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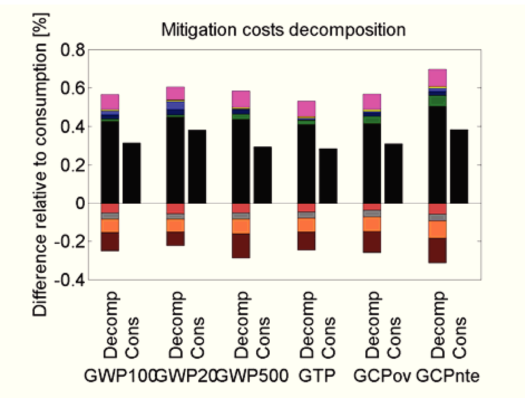

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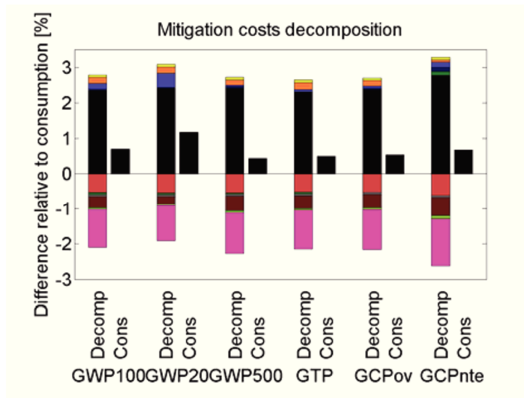

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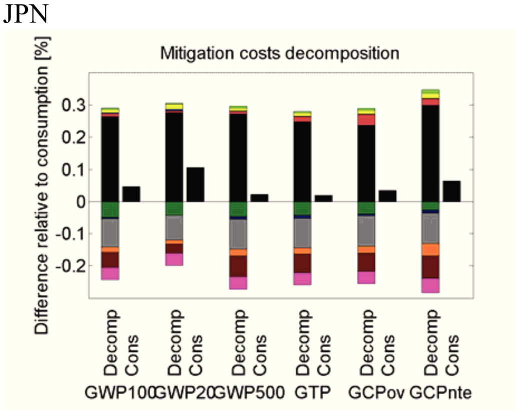

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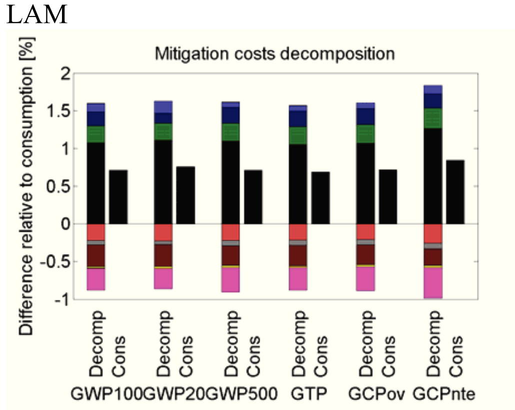

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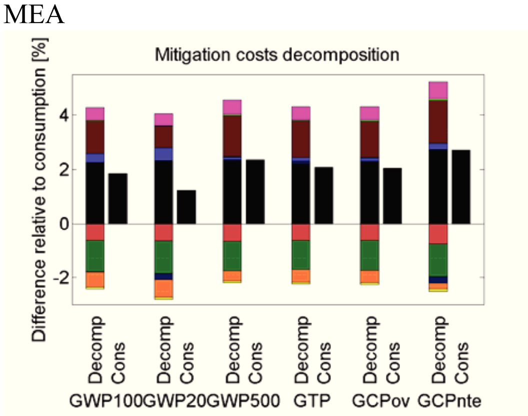

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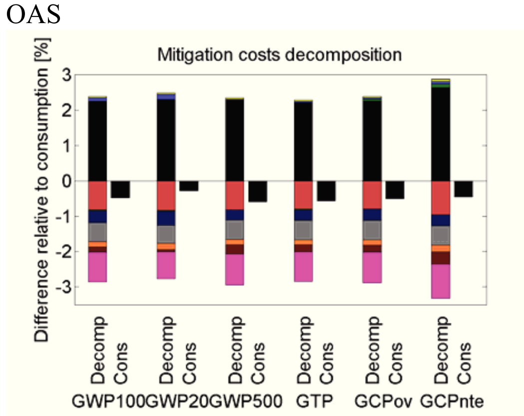

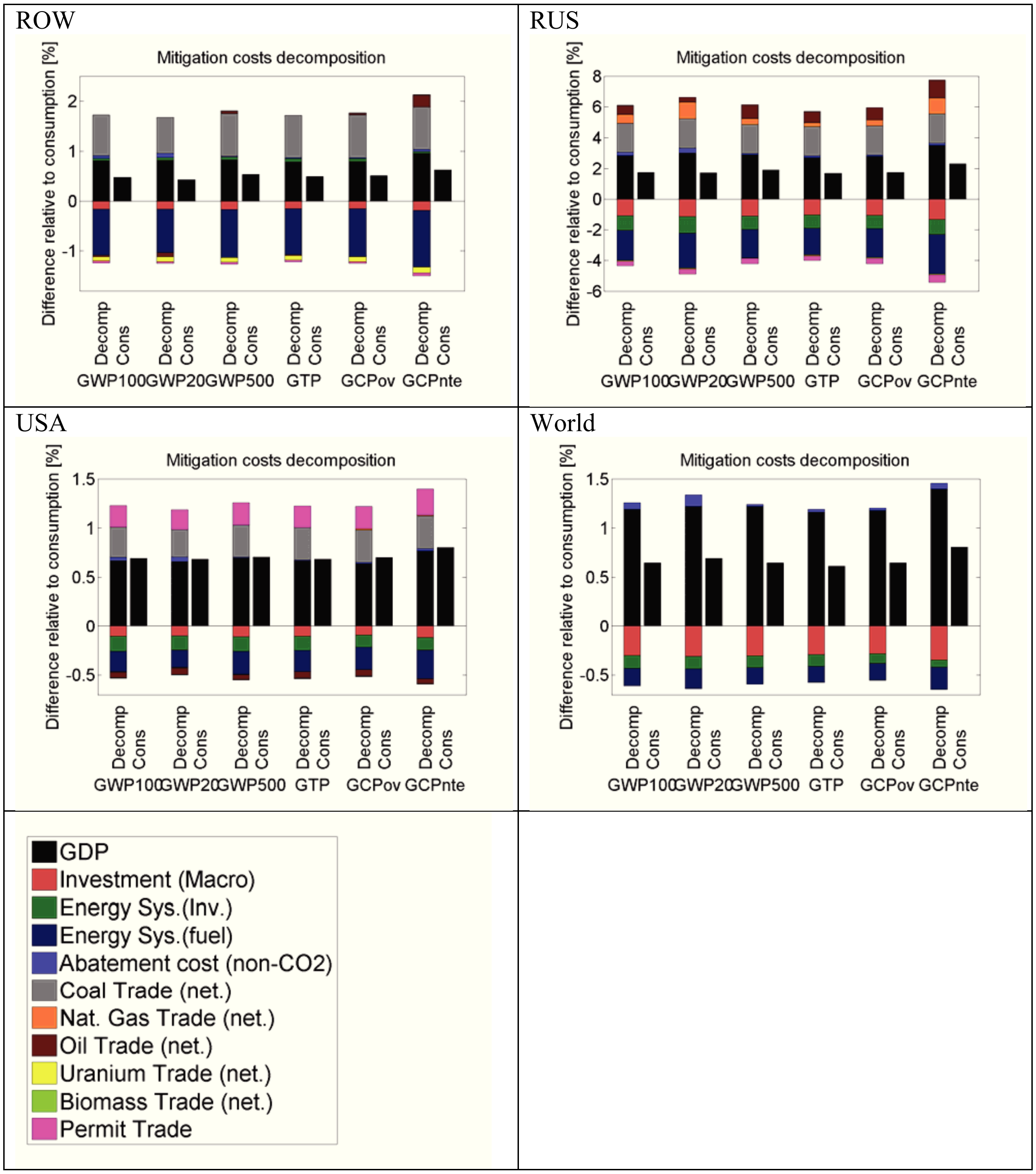

Figure S9: Decomposition of regional costs until 2050 compared to BASE. The black bar represents total mitigation costs as consumption loss relative to GDP [%]. A positive value means higher costs than the reference case, a negative value means lower costs.

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Chapter 5

The value of bioenergy in low stabilization scenarios *

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The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE

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Abstract This study investigates the use of bioenergy for achieving stringent climate stabilization targets and it analyzes the economic drivers behind the choice of bioenergy technologies. We apply the integrated assessment framework REMIND-MAgPIE to show that bioenergy, particularly if combined with carbon capture and storage (CCS) is a crucial mitigation option with high deployment levels and high technology value. If CCS is available, bioenergy is exclusively used with CCS. We find that the ability of bioenergy to provide negative emissions gives rise to a strong nexus between biomass prices and carbon prices. Ambitious climate policy could result in bioenergy prices of 70 $/GJ (or even 430 $/GJ if bioenergy potential is limited to 100 EJ/year), which indicates a strong demand for bioenergy. For low stabilization scenarios with BECCS availability, we find that the carbon value of biomass tends to exceed its pure energy value. Therefore, the driving factor behind investments into bioenergy conversion capacities for electricity and hydrogen production are the revenues generated from negative emissions, rather than from energy production. However, in REMIND modern bioenergy is predominantly used to produce low-carbon fuels, since the transport sector has significantly fewer low-carbon alternatives to biofuels than the power sector. Since negative emissions increase the amount of permissible emissions from fossil fuels, given a climate target, bioenergy acts as a complement to fossils rather than a substitute. This makes the short-term and long-term deployment of fossil fuels dependent on the long-term availability of BECCS.

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1 Introduction

Bioenergy is expected to play an important role within the portfolio of long-term greenhouse gas (GHG) mitigation options (Chum et al. 2011; Fischedick et al. 2011). Its combination with carbon capture and sequestration technologies (CCS) allows carbon to be removed from the atmosphere, making it a measure of active carbon management (Obersteiner et al. 2001; Riahi et al. 2007; Tavoni et al. 2013). This feature[1] of bioenergy with CCS (BECCS) alleviates the deep reductions of GHG emissions that are necessary to meet stringent climate change mitigation targets (van Vuuren et al. 2010a, b; Azar et al. 2010; Kriegler et al. 2013a; Edenhofer et al. 2010). Another advantage of biomass is its versatility: it can be converted into several types of secondary energy such as electricity, heat, liquid fuels, and hydrogen (Luckow et al. 2010; van Vuuren et al. 2010a). Therefore, it can serve as a flexible measure for mitigation across different sectors. The combination of both features makes it a valuable and robust mitigation option (Riahi et al. 2007). However, there are major uncertainties regarding the main factors that determine biomass deployment. First, due to uncertainty about future development of land use and agricultural production, there is a wide range of future estimates of bioenergy potential, ranging from less than 50 to several hundred EJ in 2050 (Chum et al. 2011). Furthermore, concerns about the negative impacts of large-scale biomass production on food security, biodiversity and GHG emissions exist (Wise et al. 2009; van Vuuren et al. 2010a; Creutzig et al. 2012; Popp et al. 2011, 2012, 2013). Second, there is major uncertainty about the availability of advanced second-generation bioenergy conversion technologies (Sims et al. 2010). Finally, large uncertainties remain regarding the future deployment of CCS with respect to technological challenges, constraints on storage capacities, and limited social acceptance (Zoback and Gorelick 2012).

This study argues that two key features of bioenergy—versatility and negative emissions—determine its use and value as a mitigation option. Versatility allows bioenergy to be deployed in the way most valuable for decarbonizing energy use (as measured in terms of revenues from its energy production), and its negative emissions capability suggests to use it in a way which maximizes the amount of CO_2 withdrawn from the atmosphere. In the framework of our study, the latter is incentivized by the fact that the carbon price accrues as revenue to BECCS operators for every ton of CO_2 withdrawn (carbon revenue). Concretely, we ask the following questions:

- How do the carbon and energy value of bioenergy determine its overall value for climate change mitigation?
- How does the structure of energy and carbon revenues differ across different bioenergy technologies, and how do these differences affect their deployment for different levels of climate stabilization targets?
- How does biomass deployment interact with the deployment of fossil fuels?

Based on these questions, we aim to characterize the two key economic drivers behind bioenergy use, their interplay and the potential trade-offs between them. To our knowledge, such a detailed characterization has not yet been provided in the literature. To account for the uncertainties about crucial determinants of bioenergy deployment we additionally vary the availability of biomass and CCS technology and study their impact on the mitigation strategy and its costs. We shed light on the crucial factors that determine the choice of bioenergy conversion technology if carbon and bioenergy markets are interlinked, adding to

[1] There are other options to generate net negative emissions, e.g., direct air capture technologies and afforestation. In contrast to biomass, they are not usable as primary energy carriers.

existing studies (Luckow et al. 2010; Calvin et al. 2009; van Vuuren et al. 2010a) on the preferred long-term and large-scale applications of bioenergy under climate policy.

2 Methodology

Bioenergy deployment depends on the evolution of both energy and land-use systems. Therefore, an in-depth analysis of future scenarios of bioenergy use requires modeling of the two systems. This study applies the combined model system REMIND-MAgPIE. The integrated assessment model REMIND represents the energy-economy-climate system and covers a wide range of bioenergy and competing conversion technologies. Within REMIND, the land-use sector is represented by an emulation of the high-resolution land-use model MAgPIE. This emulation focuses on bioenergy supply costs and total agricultural emissions.

2.1 The integrated assessment model REMIND

The Refined Model of Investment and technological Development (REMIND) is a global multi-regional model that assesses climate change mitigation policies over the course of the 21st century, while integrating the interactions between the economy, the energy sector, and climate change (Leimbach et al. 2010a, b; Luderer et al. 2012, 2013; Bauer et al. 2012a, b).

REMIND combines a macro-economic Ramsey-type growth model, a detailed bottom-up model of energy production and conversion, and a climate module. The macro-economy endogenously determines the demand for final energy. The final energy carriers and services are produced from primary energy using a broad set of technologies for conversion, transmission, and distribution (cf. supplementary online material (SOM) Table S2). Endogenous technology learning is assumed for solar photovoltaic and concentrating solar power as well as wind turbines (see SOM Section S1 for further information on non-biomass renewables). REMIND assumes a global storage potential for captured carbon of 3600 $GtCO_2$ and a maximal annual injection rate of 0.5 % of the regional total potential (see SOM Section S1.6 for regional potentials). Prices for fossil and biomass resources are calculated from supply cost curves. Regions interact via trading of goods and primary energy carriers, including biomass.

Bioenergy can pursue different technology routes to be converted from primary energy into several types of secondary energy carriers. Dominant technologies are biomass-to-liquid fuels B2L, BIGCC (integrated gasification combined cycle) producing electricity, and biomass-to-hydrogen (B2H2). BIGCC and B2H2 feature high capture rates (80 % and 90 %, respectively), whereas B2L maintains a lower capture rate (48 %) since a significant share of carbon is embedded in the resulting fuel. Detailed information about bioenergy conversion routes and competing technologies and their techno-economic characteristics can be found in SOM Table S3. Biomass is considered a low-carbon energy source with a credit for negative emissions from CCS in the energy system. A detailed description of the assumptions on bioenergy and the interaction of the REMIND and MAgPIE model can be found in Section 2.3 and 2.3.

The techno-economic characteristics of the technologies and the endogenously evolving prices of energy and GHG emissions determine the size and structure of the energy sector. Climate change stabilization targets are implemented by constraining radiative forcing (cf. SOM Section S2.2). The REMIND model computes the cost-effective emission mitigation with full where (abatement can be performed where it is cheapest), when (optimal timing of emission reductions and investments) and what (optimal allocation of abatement among emission sources and greenhouse gases) flexibility. Further key characteristics of the REMIND model can be found in SOM Table S1 and a full model description in Luderer et al. (2013).

2.2 The land-use model MAgPIE

The bioenergy supply prices and land-use emissions represented in REMIND are based on data from the global land-use model MAgPIE (Model of Agricultural Production and its Impact on the Environment), (Lotze-Campen et al. 2008, 2010). MAgPIE is a recursive dynamic optimization model that minimizes the total cost of production for a given amount of regional food and bioenergy demand. In order to increase total agricultural production, MAgPIE can invest either in yield-increasing technological change or in land expansion (Krause et al. 2012; Popp et al. 2011). Four categories of costs arise in the model: production costs for livestock and crop production, yield-increasing technological change costs (Dietrich et al. 2013), land conversion costs, and intraregional transport costs. A breakdown of total agricultural production costs into these categories can be found in SOM Figure S14. MAgPIE considers regional economic conditions such as demand for agricultural commodities, level of agricultural technology, and production costs as well as spatially explicit data on potential crop yields, land, and water constraints (from the dynamic vegetation model LPJmL, Bondeau et al. 2007) and derives specific land-use patterns, yields, and total costs of agricultural production. The model incorporates N_2O and CH_4 emissions from agricultural production (Bodirsky et al. 2012) as well as CO_2 emissions from land-use change (Popp et al. 2012). Since the demand for food is prescribed exogenously based on the assumed pattern of regional per capita income, there is no price response of food demand. Neither is there any underlying “food-first” policy in MAgPIE. Biomass competes with the production of food crops for land and other agricultural resources. This competition determines the biomass prices that emerge from MAgPIE. Biomass supplies specialized 2nd generation ligno-cellulosic grassy and woody bioenergy crops, i.e. miscanthus, poplar, and eucalyptus.

2.3 Representation of the land-use sector

The supply of purpose-grown ligno-cellulosic biomass in REMIND is represented by regional supply price curves that are calculated based on the price responses of MAgPIE to different biomass demand scenarios (Klein, in prep., SOM Fig. S2). Regional biomass endowments within REMIND are not limited explicitly (apart from a global limit, see below). However, there is an implicit limit, since the biomass supply curves prescribe rising prices for increasing demand. Therefore, the competitiveness of bioenergy with other energy carriers is limited. The emission baselines for CH_4, N_2O, and CO_2 from land-use and land-use changes were also obtained from MAgPIE. They are exogenously prescribed to REMIND and can be reduced according to marginal abatement cost (MAC) functions (Lucas et al. 2007). The MAC function for CO_2 abatement resulting from avoided deforestation was derived from MAgPIE by measuring the response of CO_2 emissions to varying CO_2 prices.

We use different bioenergy supply cost curves for the policy and baseline scenarios in REMIND since carbon pricing not only results in lower land-use emissions, but also increases bioenergy prices. Consistent with Wise et al. (2009) we find that pricing emissions from land-use change induces avoided deforestation. The avoided deforestation leads to an intensification rather than extensification of land for bioenergy production and thus makes it more costly to produce bioenergy. Wise et al. (2009) observes that carbon prices not only reduce deforestation but may even lead to afforestation. However, this option is not available in the current MAgPIE model. In the presence of carbon pricing, deforestation comes to a halt by 2020 in all policy scenarios. The resulting carbon emissions from land use show levels of about 4.4 GtCO2/year until 2020 and zero emissions thereafter. N_2O emissions from bioenergy production due to fertilization are covered by an emissions factor[2] of 3.7 kg CO_2 eq/GJ in REMIND. By including the emission baselines and emission factors, direct and indirect emissions caused by bioenergy deployment are fully represented and are part of the climate change stabilization target in REMIND. Therefore, emissions from the land-use sector and the energy system are valued equally.

Bioenergy is assumed to be predominantly produced from second-generation, ligno-cellulosic, purpose grown biomass, and ligno-cellulosic agricultural and forestry residues. The traditional use of biomass phases out until 2050, based on the assumption that it is replaced with modern, sustainable, and less harmful fuels as incomes rise, especially in developing countries. First-generation biofuels are expected to contribute only in the short- to mid-term and they are expected to be replaced by second-generation fuels (Sims et al. 2010). Land-use impacts, co-emissions, and competition with food production from first-generation biofuels are heavily debated (Searchinger et al. 2008; Fargione et al. 2008). REMIND assumes that only small amounts of first-generation fuels exist (less than 0.1 EJ/year globally). The model considers the low-cost potential of ligno-cellulosic agricultural and forest residues, which increases from 20 EJ/year in 2005 to 70 EJ/year in 2100 (based on Haberl 2010 and own calculations). Given the concerns about the sustainability implications of large-scale bioenergy production, REMIND assumes, by default, an upper global limit of 300 EJ/year for second-generation biomass use. This constraint is consistent with the upper end of potential 2050 deployment levels identified in Chum et al. (2011). Based on the current public debate, we consider this constraint to be a reflection of the potential institutional limitations on the widespread use of bioenergy; however, it does not reflect a limitation of bioenergy supply in the MAgPIE model. We have run the scenarios analyzed in this study with unconstrained bioenergy supply and found that bioenergy deployments in 2100 reach 355 EJ/year in the 550-FullTech scenario and 535 EJ/year in the 450 FullTech scenario. Therefore, the bioenergy constraint becomes binding at some point in the second half of the 21st century (cf. Section 3 on results).

2.4 Interaction of the models

For the EMF27 scenario analysis the three models REMIND, MAgPIE and MAGICC (Meinshausen et al. 2011) were run consecutively (cf. SOM Figure S4). In a first step REMIND calculates the optimal mitigation strategy for the energy system. Using an emulation of the MAgPIE model REMIND takes into account the bioenergy supply curves, land use emissions and land use based mitigation potentials as described above. REMIND also includes an emulator of the MAGICC model to relate emissions to radiative forcing and temperature. Results from the land use and climate emulation in REMIND and from the subsequent post-runs in MAgPIE and MAGICC are very close to each other. The latter are reported to the EMF27 database.

[2] This emission factor was estimated from MAgPIE results and assuming a global warming potential of 298 for N_2O. Van Vuuren et al. 2010c report a similar value of 2.93 kg CO_2 eq/GJ.

2.5 Scenario definition

This analysis focuses on the EMF27 scenarios that combine different climate targets with the availability of CCS and high and low bioenergy potential. The EMF 27 scenarios cover three types of climate targets: baseline scenarios without climate protection targets (referred to as “Base”), 3.7 W/m^2 forcing stabilization targets (not to exceed, referred to as “550”), and 2.8 W/m^2 forcing targets with overshoot (referred to as “450”). Scenarios with CCS and an upper limit of 300 EJ/year for biomass are labeled “FullTech”. Scenarios imposing a limit of 100 EJ/year on global bioenergy potential are referred to as “LimBio”. If a scenario excludes CCS, it is labeled “NoCCS”. A description of the full portfolio of EMF27 scenarios is given in Kriegler et al. (2013b).

3 Results

The general finding across all scenarios shows that bioenergy is one of the major mitigation options in stringent climate policy scenarios. This paramount importance of bioenergy for achieving low-stabilization targets can be attributed to its two key characteristics: its versatility for producing different secondary energy carriers, and the option to create negative emissions by combining bioenergy with CCS. Section 3.1 and 3.2 focus on the deployment of bioenergy in the energy supply mix, and how this relates to its versatility and negative emissions capability. Section 3.3 and 3.4 investigate the value of and economic drivers behind bioenergy deployment in climate policy scenarios.

3.1 The contribution of bioenergy to primary energy supply

The REMIND baseline scenario is characterized by a strong reliance on fossil fuels. Traditional biomass is used in the first half of the century, but modern bioenergy use remains insignificant. While total primary energy demand continues to increase, deployment of fossil fuels peaks in 2070 due to increasing scarcity and is subsequently replaced with renewable sources. Solar and wind energy contribute to electricity production, whereas bioenergy replaces fossil transport fuels.

As Fig. 1 (left and middle) shows, climate policy leads to earlier deployment of bioenergy and much higher long-term deployment, reaching 300 EJ/year. While bioenergy contributes substantially to global primary energy supply in all scenarios, primary energy mixes vary considerably depending on the stringency of the climate target and the availability of technology. All climate policy scenarios show a reduction of final energy demand compared to the baseline (−16 % to −28 %, cf. SOM Figure S5), which results in a substantial decrease in primary energy demand.[3] In all climate policy scenarios, the use of conventional coal without CCS is phased out quickly after 2010 and decreases to nearly zero by 2040. In addition, only negligible or relatively small coal use with CCS is observed across the scenarios. The 550 FullTech scenario allows for higher deployment levels of oil and gas throughout the whole century compared to the 450 FullTech case. In both FullTech mitigation scenarios, gas with CCS is a mid-term mitigation option with maximal deployment

[3] The direct equivalent method was used for primary energy accounting. Since it accounts one unit of non-biomass renewable or nuclear energy for roughly three units of fossil fuels in electricity production, it tends to understate the contribution of renewables or nuclear in primary energy supply. Reductions in primary energy are partly due to a shift from fossil fuel combustion to non-biomasss renewables and nuclear energy.

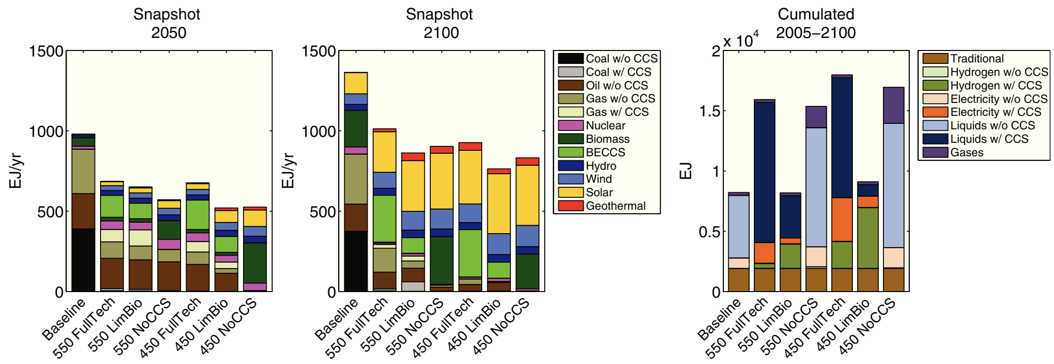

Fig. 1 Demand for primary energy: in 2050 (*left*) and 2100 (*middle*); demand for bioenergy across technologies cumulated from 2005 to 2100 (*right*)

around 2045. At the end of the century, fossil fuels account for approximately 30 % (300 EJ) in the 550 FullTech scenario and only 10 % (90 EJ) in the 450 FullTech scenario. In all policy scenarios, the expansion of modern bioenergy use begins around 2030, about 30 years earlier than in the baseline, and evolves dynamically thereafter. The maximum potential is reached between 2040 (100 EJ in 450-LimBio) and 2080 (300 EJ in 550-FullTech). BECCS conversion routes are so attractive that bioenergy without CCS is crowded out. New conversion capacities for bioenergy are exclusively built with CCS in all policy scenarios that allow for CCS. In contrast, fossil CCS is less favored as it entails residual emissions in the REMIND model. In both FullTech policy scenarios, BECCS makes up approximately 30 % (300 EJ) of primary energy at the end of the century.

In all policy scenarios, the non-biomass renewable energies - solar, wind, and hydro - have a dominant share in the power supply after 2060, of which solar comprises the majority. By 2100, their contribution reaches approximately 41 % (550-FullTech) to 76 % (450-LimBio) of primary energy supply.

In the 450/550-FullTech scenarios fossil fuels and industry emit 1670/2290 $GtCO_2$ from 2005 to 2100, of which 830/610 $GtCO_2$ (50/27 %) are withdrawn by BECCS, resulting in 840/1680 $GtCO_2$ deposited in the atmosphere by 2100. Together with fossil CCS 950/770 $GtCO_2$ have been captured by 2100 (SOM Section S2.3 and S2.4).

3.2 Bioenergy: a versatile energy carrier

Due to its versatility, bioenergy assumes a unique position among non-fossil energy carriers. In contrast to nuclear or non-biomass renewables, it can be converted into different types of secondary energy. Figure 1 (right) depicts the demand of primary bioenergy for those types of secondary energy cumulated for 2005–2100. Modern bioenergy is mainly deployed in the second half of the century. The exogenously prescribed phase out of traditional biomass is not varied across scenarios.

In almost all scenarios including the baseline, bioenergy is predominantly used to produce liquid fuels. In the baseline scenario, biofuel is a substitute for increasingly scarce and costly oil in the second half of the century. Under climate policy, biofuel production with CCS has two purposes. First, it lowers emissions in the transportation sector, for which other decarbonization methods, such as electrification, are rather costly. Second, it produces negative emissions, which offset emissions from other sources (cf. Section 3.3). Only the 450-ppm scenarios (FullTech and LimBio) show capacities for dedicated electricity production from biomass using BIGCC with CCS. In all other scenarios the small amounts of bioenergy demand for electricity accompanying the dominant demand for liquids is due to the fact that electricity is a byproduct of the biomass liquefaction process represented in REMIND (cf. SOM Table S2). The BIGCC and B2H2 processes feature higher capture rates and, therefore, enable the higher negative emissions that are required in the more stringent mitigation scenarios. In general, tightening the climate target or restricting the bioenergy potential increases the deployment of technologies with higher capture rates, in order to maximize negative emissions per unit of primary bioenergy used. Consequently, the shares of BIGCC (80 % capture rate) and/or hydrogen production (90 % capture rate) increase from 550-FullTech to 450-FullTech, from 550-FullTech to 550-LimBio, from 450-FullTech to 450-LimBio, and from 550-LimBio to 450-LimBio. Kriegler et al. (2013a) also observe a higher share of B2H2 and BIGCC compared to B2L due to tighter bioenergy supply limited to 200 EJ/year.

3.3 The value of bioenergy for climate change mitigation

The following sections show that bioenergy has a high value for climate mitigation. As a direct reflection of this, mitigation costs, an indicator of the economic challenges resulting from climate policy, rise sharply if bioenergy or CCS are limited (Fig. 2). This indicates that without bioenergy and CCS, it is difficult to achieve low stabilization targets.

Aggregate mitigation costs are expressed in terms of consumption losses between a climate policy scenario and the corresponding baseline, in net present value terms for the period 2005–2100 and discounted at 5 % per year, as a share of net present value consumption in the baseline. We find that mitigation costs depend strongly on the climate target as well as the abundance of bioenergy and the availability of CCS technologies. Increasing the stringency of the climate target from 550 ppm to 450 ppm results in almost a doubling of mitigation costs from 1.8 % to 3.1 %. The unavailability of CCS increases mitigation costs more (to 2.7 % for 550-ppm and 10.5 % for 450-ppm) than lowering the bioenergy potential from 300 EJ/year to 100 EJ/year (to 2.3 % and 5.7 % respectively). The costs for all 550-ppm scenarios lie below the 450-ppm policy costs. In the 450-ppm scenario, costs almost double (to 5.7 %) if bioenergy supply is limited to 100 EJ/year and more than triple (to 10.5 %) if CCS is not available. The value of bioenergy and BECCS increases with the stringency of the mitigation target, and is particularly important for low stabilization at 450 ppm CO_2e.

BECCS is particularly valuable because its negative emissions provide an additional degree of freedom for the amount and timing of emission reductions (Kriegler et al. 2013a). Since emissions from fossil fuel combustion in earlier periods can be compensated by negative emissions at a later stage (up to 50 % in the 450-FullTech scenario), negative emissions allow for the postponement of some emission reductions in the short-term and the preservation of some residual emissions in the long run. This is even more significant if overshooting of the stabilization target (in terms of radiative forcing) is allowed before 2100. Figure 2 illustrates this emission dynamics and the challenges associated with climate stabilization with full and limited technology portfolios. The graph shows CO_2 emissions over time from fossil fuel and industry with (top left) and without accounting (top right) for negative emissions from BECCS as well as the resulting CO_2 prices (bottom left). Pathways of net emissions do not depend on the availability of biomass or CCS in the 550-ppm case. In the 450-ppm scenario, BECCS in the second half of the century compensates for the emissions of the preceding decades. Limiting the bioenergy potential to 100 EJ/year or excluding CCS strongly reduces this inter-temporal flexibility. An immediate and rapid restructuring of the energy system is required in the early decades since strong overshooting

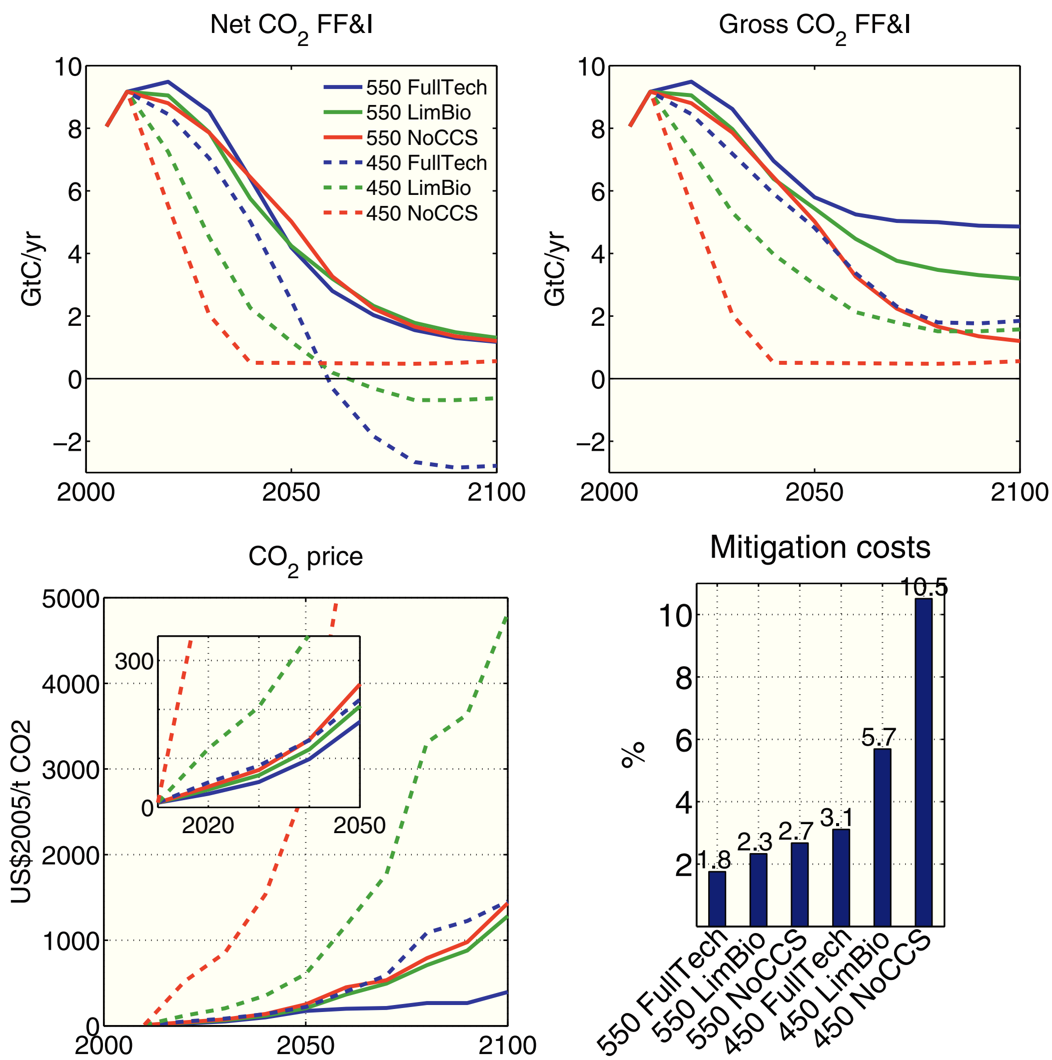

Fig. 2 Dynamics of mitigation across scenarios: CO_2 emissions from fossil fuel and industry (FF&I) including negative emissions (*top left*) and without negative emissions (*top right*); CO_2 prices over time (*bottom right*); mitigation costs (discounted and cumulated consumption losses 2005–2100), (*bottom right*)

of the forcing target (by 0.7 W/m^2 as observed in the 450-FullTech scenario), is no longer possible (0.3 W/m^2 in the 450-NoCCS scenario). Consequently, carbon prices as high as 120 \$/tCO_2 in 2020 (520 \$/tCO_2 with NoCCS), compared to 50 \$/tCO_2 in the FullTech scenario, are required to trigger this early transformation and to reach the 450-ppm target.

Figure 3 (left) shows that these emission dynamics directly translate into a relationship between the pathways of fossil fuels and bioenergy deployment making the short and long-term deployment of fossil fuels dependent on the long-term potential of biomass. Figure 3 (right) depicts the cumulated amounts (from 2005 to 2100) of fossil fuels and bioenergy for scenarios with different bioenergy availabilities scaled to the 450-FullTech scenario. Comparing the 450-LimBio with the 450-FullTech case shows the simultaneous increase of cumulated fossil fuel and bioenergy demand. Due to the creation of negative emissions, more biomass use allows for higher deployment of fossil energy. This leads to the following conclusion: while biomass is an important substitute for fossil fuels in climate mitigation scenarios, given a climate target it also displays characteristics of a complement to fossil fuels.

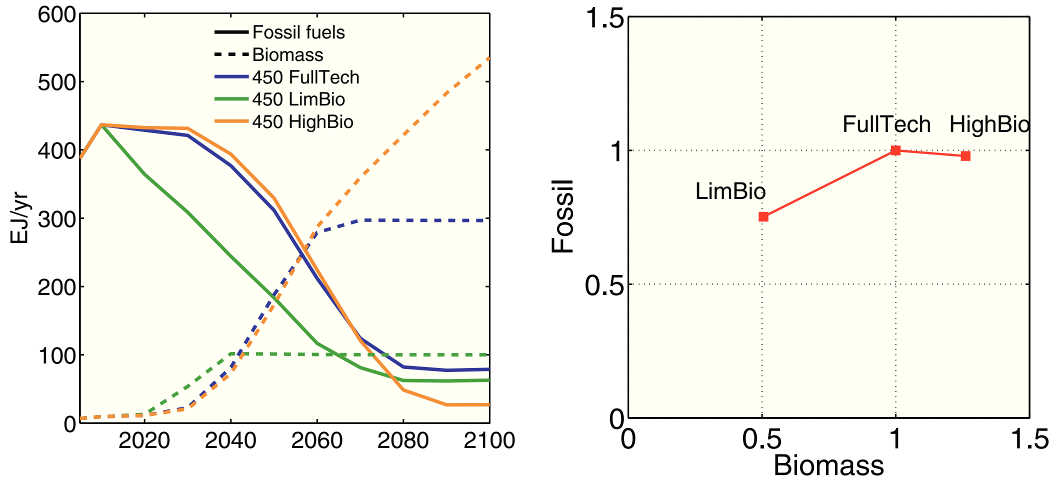

Fig. 3 Demand for bioenergy and fossil fuels over time (*left*) and cumulated from 2005–2100 scaled to the 450-FullTech scenario (*right*)

Figure 4 shows the additional 450-HighBio scenario (not part of EMF27 portfolio) which omits the 300 EJ/year constraint on global bioenergy deployment. Although the bioenergy demand strongly exceeds 300 EJ/year the corresponding amount of fossil fuels does not increase further. This is the consequence of assuming a physical limitation of the injection rate for captured carbon in REMIND. Since this limit is reached in 2060 (450-FullTech), removing the bioenergy-constraint in the 450-HighBio scenario cannot provide additional negative emissions and there is no room for additional fossil fuels. Thus, the short to long-term deployment of fossil fuels and BECCS technologies additionally depend on the rate at which CO_2 can be sequestered into geological reservoirs.

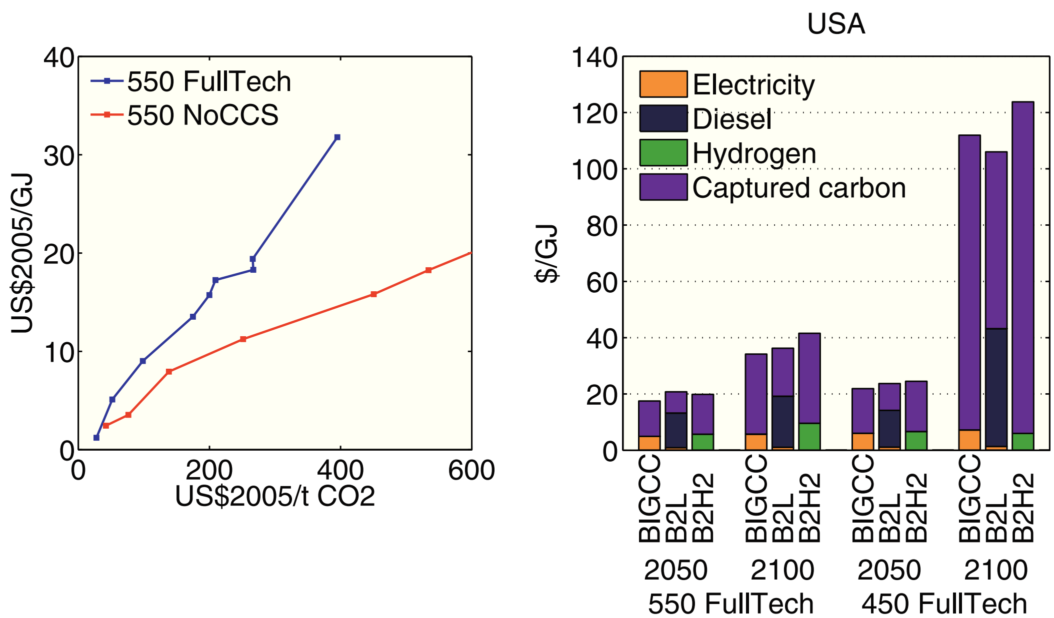

Fig. 4 Value of energy versus value of carbon: global average bioenergy price versus carbon price (*left*). Revenues from energy production and negative emissions across technologies for USA (*right*)

3.4 The relation between bioenergy and carbon markets

Maintaining today's fossil fuel deployment over the next decades under stringent climate policies induces a strong demand for BECCS in the second half of the century. This is reflected by the strongly increasing prices for biomass. While bioenergy prices in the Base-FullTech scenario range between 1 $/GJ in 2010 and 12 $/GJ in 2100, prices reach 32 $/GJ in the 550-ppm scenario and 73 $/GJ in the 450-FullTech scenario in 2100. Limiting bioenergy potential or excluding CCS increases bioenergy prices to 105 $/GJ and 431 $/GJ, respectively. Average production costs of bioenergy are much lower (around 6 $/GJ) indicating substantial revenues for bioenergy producers.

Figure 4 (left) reveals a strong correlation between carbon prices and bioenergy prices. This is not surprising: with increasing carbon prices, the incentive to replace fossil fuels with bioenergy increases, as do potential revenues from BECCS-generated negative emissions. The dependence of bioenergy prices on carbon prices is stronger in scenarios with CCS and somewhat weaker in the NoCCS scenario. In the climate mitigation scenarios, the value of bioenergy is determined by both its energy value *and* the value of potential negative emissions. An analysis of the revenues gained from biomass conversion demonstrates that under stringent climate targets, and in the presence of BECCS, the value of negative emissions tends to dominate over the value of the energy.

Figure 4 (right) shows the revenues from secondary energy production and captured carbon per unit of primary energy input for different BECCS power plants in 2050 and 2100 for the US and for the 450 and 550-FullTech scenario. In both scenarios, a major share of revenues from BIGCC and B2H2 plants is gained from capturing carbon, whereas revenues from energy production are relatively low. This effect is stronger at higher carbon prices (550 vs. 450 and 2050 vs. 2100). Compared to electricity and hydrogen, revenues from diesel are significantly higher since the transportation sector has fewer low-carbon alternatives to biomass than the electricity sector. Fossil liquids prices increase due to entailed carbon emissions. This drives up the demand for biofuels and the resulting prices for biofuels (cf. SOM Fig. S12 and Fig. S13 for a regional breakdown of revenues and liquid fuel prices). Thus, the B2L technology is attractive despite its lower capture rate. Only in scenarios with high carbon prices (LimBio vs. FullTech, 450 ppm vs. 550 ppm) technologies with higher capture rates become more favorable. The driving factor for building bioenergy conversion capacities for electricity and hydrogen production are the revenues generated from negative emissions, rather than from energy production.

4 Summary and conclusion

The potentially negative carbon content of biomass has far-reaching consequences for mitigation strategies, mitigation costs and bioenergy deployment. Our analysis shows that BECCS can be a crucial mitigation option with high deployment levels and a high technology value, particularly for low stabilization targets. In our model results, modern bioenergy is exclusively used with CCS if this technology is available. Not having BECCS available strongly increases mitigation costs.

BECCS has impact on the timing and dynamics of emission reductions over the course of the century. Negative emissions are valuable because they increase the amount of permissible carbon emissions from fossil fuels and therefore allow postponing some emissions reductions in the short-term. Thus, for a given climate target, bioenergy acts as a complement to fossils rather than a substitute. Postponing emission reductions turns this intertemporal flexibility into a commitment since the prolonged *short-term* deployment of fossil fuels rely on the *long-term* potential of biomass *and* the availability of CCS. Given the uncertainties about CCS technology and the concerns about the sustainability of large-scale production of bioenergy, a strong reliance on the availability of these two options could be a risky strategy.

The potential of biomass to provide negative emissions establishes a strong link between bioenergy prices and carbon prices. For low stabilization scenarios with BECCS availability, we find that the carbon value of biomass tends to exceed its pure energy value. This has consequences for the choice of BECCS technologies: with rising carbon price the capture rate becomes the crucial deciding factor in terms of which conversion routes are taken. High carbon prices (as observed in the LimBio scenarios) induce investments in technologies that would not be built for the purpose of energy production. In our scenarios these are electricity and hydrogen. However, except in the 450-LimBio scenario exhibiting higher carbon prices than all other CCS-scenarios, bioenergy is predominantly used to produce low-carbon fuels, since the transport sector has significantly fewer low-carbon alternatives to biofuels than the power sector.

The price link has another consequence: as this study shows, imposing stringent climate targets induces a strong demand for BECCS and a high willingness-to-pay for biomass. Postponing emission reductions will further increase this demand-pull for biomass. Thus, a high pressure on the agricultural sector can be expected under stringent climate policy even if production costs of purpose-grown biomass were high. In our analysis, biomass prices exceed average production costs, giving rise to considerable land rents for producers. The resulting large-scale bioenergy production potentially has unintended negative impacts on land-use systems, such as competition with food production, reduction of biodiversity, and additional GHG emissions (Wise et al. 2009; Searchinger et al. 2008; Fargione et al. 2008). Imposing sustainability constraints on the production of bioenergy likely will limit the potential of bioenergy (Haberl et al. 2010; van Vuuren et al. 2009) as a mitigation option. Therefore, further research is needed to study the potentially far-reaching implications of connecting agricultural, energy and carbon markets. In particular, unintended side effects should be included into the assessment of bioenergy as a mitigation measure. The investigation of this climate policy induced land-energy nexus requires an integrated assessment based on fully coupled energy-economy and land use models.

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Supporting Online Material for the Climatic Change manuscript submission

"The value of bioenergy in low stabilization scenarios: an assessment using ReMIND-MAgPIE"

by David Klein, Gunnar Luderer, Elmar Kriegler, Jessica Strefler, Nico Bauer, Alexander Popp, Marian Leimbach, Jan Philipp Dietrich, Florian Humpenöder, Hermann Lotze-Campen, Ottmar Edenhofer

1 Additional model description

The full model documentation can be found in Luderer 2013: http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/description-of-remind-v1.5

1.1 Key characteristics of the REMIND model

Table S1: ***Key characteristics of the REMIND model and its implementation of climate policy***

Model feature	Implementation in ReMIND-R Version 1.5
Macro-economic core and solution concept	Intertemporal optimization: Ramsey-type growth model, Negishi approach for regional aggregation
Substitution possibilities within the macro-economy & sectoral coverage	Nested CES function for production of generic consumption good from factors capital, labor, and different end-use energy types (electricity, stationary non-electric energy, non-electric energy used for transport).
Link between energy system and macro-economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Energy system and macro-economy are optimized jointly.
Production function in the energy system & substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors) introduce convexities. Adjustment costs on the rate of capacity expansion penalize rapid deployment.
Technological Change & Learning	Learning by doing (LbD) for wind and solar power. A global learning curve is assumed. LbD spillovers are internalized. Labor productivity and energy efficiency improvements are prescribed exogenously.
International trade	Global markets for coal, oil, gas and biomass; generic consumption good and capital; emissions permits. Interregional trade of captured CO_2 is not considered.
Discounting	The constant rate of pure time preference in the iso-elastic welfare function is set to 3%. The discount rate emerges endogenously on the global capital markets. In line with the Keynes-Ramsey-Rule, with an intertemporal elasticity of substitution of one and an average rate of increase of global per capita incomes of around 3%, the discount rate is between 5 and 7%.
Emissions and forcing representation	CO_2 emissions from fossil fuel use are modeled by source. A marginal abatement cost curve (MAC) for land use CO_2 emissions is used to capture the potential for reduced deforestation. MACs for CH_4 and N_2O emissions integrate abatement potentials in the energy and land use sectors. N_2O emissions from bioenergy use are modeled explicitly (3.7 kgCeq/GJ of biomass primary energy). CH_4 emissions from fossil fuel extraction depend on the amount of fossils extracted. CO_2 emissions from cement production and CH_4 and N_2O emissions from waste are estimated using a simple econometric model, where per capita emisisons depend

on per capita capital investments or GDP, respectively. SO_2 and carbonaceous aerosol emissions from fossil fuel combustion are modeled by source. Emissions of HFCs, PFCs, SF_6, Montreal gases, ozone precursors (CO, VOC, NO_x) and biomass burning aerosols are treated exogenously. Radiative forcing from nitrate aerosols, mineral dust, and land albedo changes is assumed exogenously.

Land use

Land use is not modeled explicitly (see manuscript Section 2.3 and 2.4 and SI Figure S4). The bioenergy supply curve is based on MAgPIE data. A marginal abatement cost curve for REDD is included in the model. The option of afforestation is not represented. Interactions between deforestation and bioenergy use are not explicitly captured, but bioenergy use is capped at 300 EJ/yr or 100 EJ/yr depending on the scenario. This limit applies to modern second-generation biomass including residues, but not including the traditional use of biomass.

Implementation of the CO_2e stabilization target

The CO_2e(quivalent) constraint is imposed on total anthropogenic forcing (a detailed description can be found in SI Section 2.2). This leads to a uniform shadow price for the endogenous Kyoto gas emissions in the model (CO_2, CH_4, N_2O). The price is established under full when (time), where (region) and what (GHG) flexibility to meet the radiative forcing constraint.

The 450 ppm CO_2e target is imposed in the year 2100, with overshoot allowed before 2100. The REMIND model runs until 2150 to ensure that the 21st century emissions trajectory will not violate the target beyond 2100.

Implementation of emissions taxes

CO_2, N_2O and CH_4 from the energy and land use sectors are subjected to the emissions tax. The tax level for a ton of carbon dioxide (equivalent) is converted into N_2O and CH_4 using their 100 year global warming potentials reported in the 4th Assessment Report of the IPCC.

1.2 Energy conversion routes

Table S2*: Conversion Technologies in ReMIND*

		PRIMARY ENERGY CARRIERS						
		Exhaustible				Renewable		
		Coal	**Oil**	**Gas**	**Uranium**	**Solar, Wind, Hydro**	**Geothermal**	**Biomass**
SECONDARY ENERGY CARRIERS	**Electricity**	PC, IGCC	DOT	NGCC	LWR	SPV, WT, Hydro, *CSP*	HDR	BIGCC
	H2	C2H2		SMR				B2H2
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid	C2L	Refin.					B2L

	fuels							Bioethanol
	Other Liquids		Refin.					
	Solids	CoalTR						BioTR

Abbreviations:
B2G = biogas
B2H2 = biomass to H2
B2L = biomass to liquids
BIGCC = Biomass IGCC
BioCHP = biomass combined heat and power
BioEthanol = biomass to ethanol
BioHP = biomass heating plant
BioTR = biomass transformation
C2G = coal to gas
C2H2 = coal to H2
C2L = coal to liquids
CoalCHP = coal combined hat power
CoalHP = coal heating plant
CoalTR = coal transformation
DOT = diesel oil turbine
GT = gas turbine GasCHP = Gas combined heat power
GasHP= gas heating plant
GasTR = gas transformation
GeoHP = heating pump
HDR = hot-dry-rock
Hydro = hydro power
IGCC = integrated coal gasification combined cycle
LWR = light water reactor
NGCC = natural gas combined cycle
PC = conventional coal power plant
Refin. = Refinery
SMR = steam methane reforming
SPV = solar photo voltaic
WT = wind turbine

1.3 Techno-economic data of bioenergy technologies

Table S3: ***Techno-economic parameters of biomass conversion technologies (Iwasaki, 2003; Hamelinck, 2004; Ragettli, 2007; Schulz et al., 2007; Uddin and Barreto, 2007; Takeshita and Yaaij, 2006; Gül et al., 2008; Brown et al., 2009; Klimantos et al., 2009) and selected competing technologies represented in the integrated assessment model REMIND1.5.***

	Investment costs [US$2005/kW]	O&M costs [$/GJ]	Conversion efficiency	Couple production*	Capture rate	Learning
NGCC	650	0.95	0.56			
NGCC CCS	1100	1.62	0.48		90 %	
NGT	350	1.47	0.38			
GasCHP	800	2.38	0.45	0.42 Heat		
GasHP	300	1.35	0.75			
Gas2H2	498	0.58	0.73	-0.01 Electr.		
Gas2H2 CCS	552	0.66	0.70	-0.04 Electr.	90 %	
O2Ld	494	0.84	0.75	0.21 Diesel		
O2Lp	222	0.55	0.75	0.21 Petrol		
IGCC	1650	3.09	0.43			
IGCC CCS	2050	4.20	0.38		90 %	
PC	1400	2.57	0.45			
PC CCS	2400	4.69	0.36		90 %	
PC CCS ox	2150	4.33	0.37		99 %	
CoalCHP	1350	3.74	0.40			
CoalHP	400	1.90	0.70			
C2L	1450	3.85	0.40			

C2L CCS	1520	4.54	0.40		70 %	
C2H2	1260	1.64	0.59	0.08 Electr.		
C2H2 CCS	1430	1.87	0.57	0.05 Electr.	90 %	
BioTr	150	0.00	1.00			
BioSolids	225	0.24	0.90			
BioCHP	1375	4.75	0.43	0.72 Heat		
BioHP	400	2.06	0.80			
BIGCC	1860	3.95	0.42			
BiGCC CCS	2560	5.66	0.31		80 %	
B2G	1000	1.74	0.55			
B2H2	1400	5.27	0.61			
B2H2 CCS	1700	6.33	0.55		90 %	
B2Lp	2380	8.95	0.36	0.15 Electr.		
B2Ld	2500	3.48	0.40	0.16 Electr.		
B2Ld CCS	3000	4.52	0.41	0.14 Electr.	48 %	
Hydro	2300	1.46				
Wind	1400	0.89				Floor: 900 $/kW; Learning rate: 12% of costs above floor
SPV	5300	3.36				Floor: 600 $/kW; Learning rate: 20% of costs above floor
CSP	9500	9.04				Floor: 1900 $/kW; Learning rate: 9% of costs above floor

Abbreviations:
NGCC: Natural gas combined cycle
NGCC CCS: NGCC with CCS
NGT: Natural gas turbine
GasCHP: Natural gas combined heat and power
GasHP: Natural gas heating plant
Gas2H2: Natural gas to hydrogen
Gas2H2 CCS: Gas2H2 with CCS
O2Ld: Refinery from crude oil to diesel
O2Lp: Refinery from crude oil to petrol
IGCC: Coal integrated gasification combined cycle
IGCC CCS: IGCC with CCS
PC: Pulverized coal power plant
PC CCS: PC with CCS
PC CCS ox: PC with CCS using oxy-fuel
CoalCHP: Coal combined heat and power
CoalHP: Coal heating plant
C2L: Coal to diesel
C2L CCS: C2L with CCS
C2H2: Coal to hydrogen
C2H2 CCS: C2H2 with CCS
BioTr: Traditional biomass usage
BioSolids: Modern solid production from biomass
BioCHP: Biomass combined heat and power
BioHP: Biomass heating plant
BIGCC: Biomass IGCC power plant
BiGCC CCS: BIGCC with CCS
B2G: Biomass to gas
B2H2: Biomass to hydrogen
B2H2 CCS: B2H2 with CCS
B2Lp: Biomass to diesel
B2Ld: Biomass to petrol
B2Ld CCS: B2Ld with CCS
Hydro: Hydro power plant
Wind: Wind turbine (combined on- and offshore)
SPV: Photovoltaic
CSP: Concentrated solar power plant

* defined as units of couple product that can be additionally produced (or is consumed in case of negative vale) per unit of main product.

1.4 Regional breakdown of renewable energy potentials

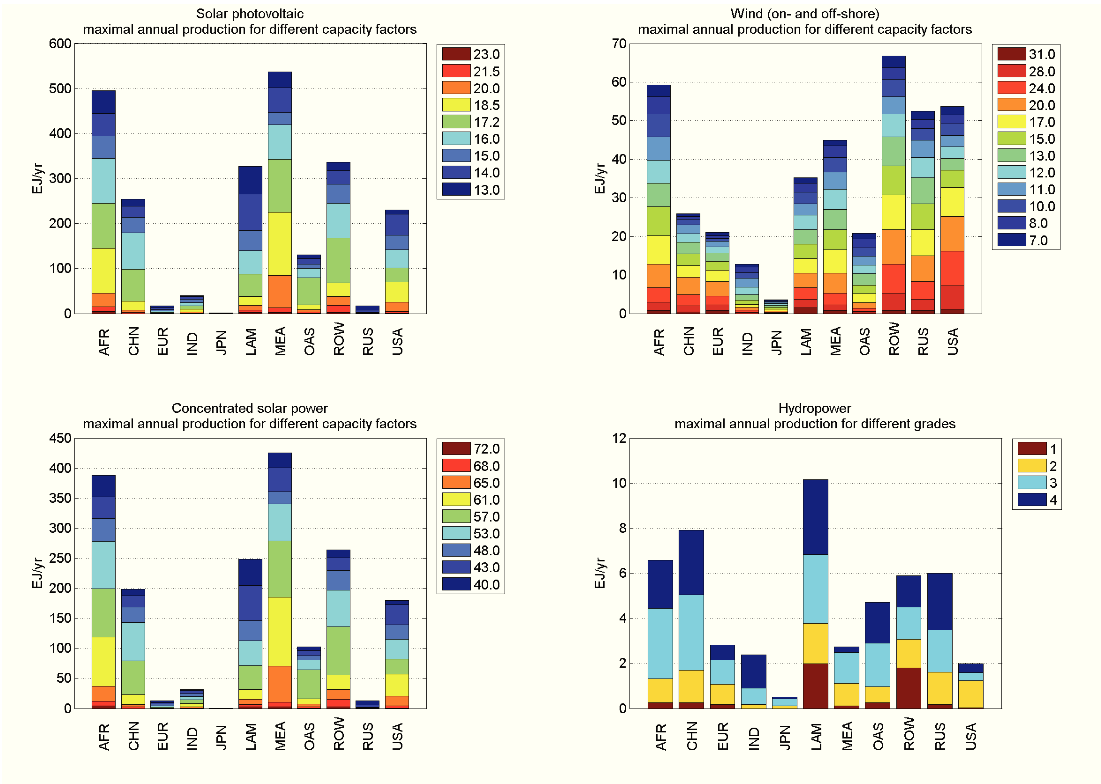


Figure S1: Maximal annual production across regions and grades for solar photovoltaic, concentrated solar power, wind (on-shore and off-shore combined) and hydro power.

The resource potentials for non-biomass renewables are modeled using region-specific potentials. For each renewable energy type, the potentials are classified into different grades, which are specified by capacity factors. Superior grades have higher capacity factors, which correspond to more full-load hours per year. This implies that more energy is produced for a given installed capacity. Therefore, the grade structure leads to a gradual expansion of renewable energy deployment over time as a result of optimization.

1.5 Bioenergy supply price curves

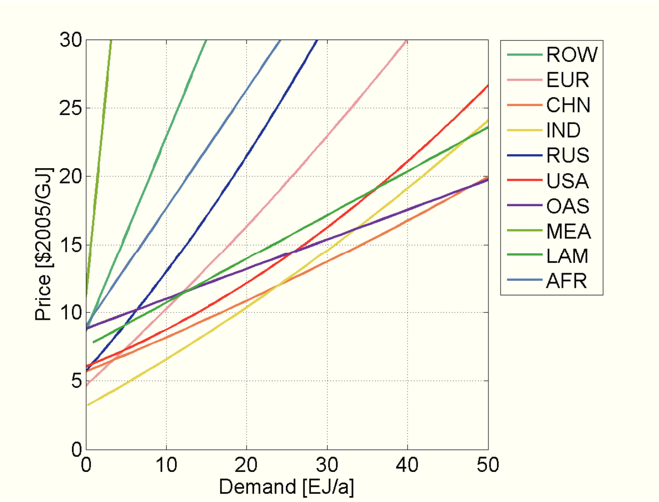


Figure S2: ***Regional price curves for the supply of 2nd generation purpose grown bioenergy. For Japan it is assumed that due to space limitation in the agricultural system there is no potential to produce purpose grown biomass.***

1.6 Regional carbon storage potentials

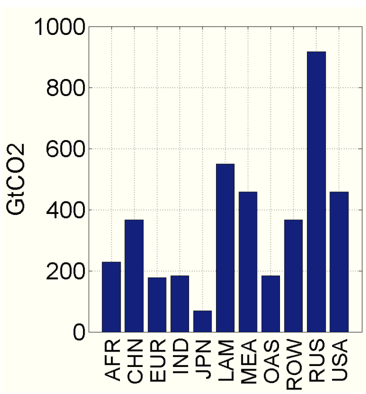


Figure S3: ***Regional storage potential for carbon, for exact numbers see Table S4 below.***

Table S4: ***Assumptions on regional storage potentials in GtCO₂***

	AFR	CHN	EUR	IND	JPN	LAM	MEA	OAS	ROW	RUS	USA	World
Total potential	229	367	178	183	69	550	458	183	367	917	458	3959
Realizable potential*	109	174	84	87	33	261	218	87	174	435	218	1881

* Limit is defined by the maximal annual injection rate of 0.5 % of the regional total potential and the timespan of 95 years (2005-2100).

The storage of CO_2 is described by three main characteristics. First, the levelized costs for transporting and injecting the CO_2 are at 9US$ per tCO_2. Second, the storage potentials are limited for each region. The assumptions are derived from the IEA report on CCS (IEA 2008). This assessment is relatively optimistic and therefore the most uncertain deposits have been excluded.

The total global storage volume is limited to 3959 $GtCO_2$ (1100GtC). Third, the annual injection rate in each region is limited to 0.5% of the total storage potential. This assumption reflects that storage sites cannot be filled with full temporal flexibility. In order not to over use storage sites and maintain the storage integrity we apply this limit. Geo-physical factors that rationalize this constraint are the local pressure increase that is induced at the location of the injection.

1.7 Nuclear technology and uranium resource potential

For the present study we assume 23MtU of global uranium potential with increasing extraction costs up to 260US$ per tU. Reprocessing and fast breeding reactors are not considered here. We only assume once-trough reactor types. We do not assume fuel recycling for reasons of operational safety and non-proliferation. The fast breeder technology is not assumed to be available because of reasons of technical issues, operational safety, cost, and non-proliferation. The potential of 23 MtU comprises all conventional resources including undiscovered. We assumed 17 MtU of conventional resources that were identified in NEA (2010) and WEC (2010), c.f. Table S5. To account for the large uncertainties about unconventional uranium resources we only consider a share of 6 MtU to be available in future. This adds to a global total portential of 23 MtU that is assumed in the ReMIND model.

Table S5: ***Assumptions on global uranium resources***

		BGR (2010)	NEA (2010)	WEC (2010)
Identified Resource	< 80 $US per kg	2.5	3.7	
	< 130 $US per kg		1.7	5.4
	< 260 $US per kg	3.8	0.9	0.9
Undiscovered	Prognosticated	2.9	2.9	6.8
Resource	Speculative	3.9	7.5	3.6
Unconventional			< 22	10-22

1.8 Model framework and interaction between the models

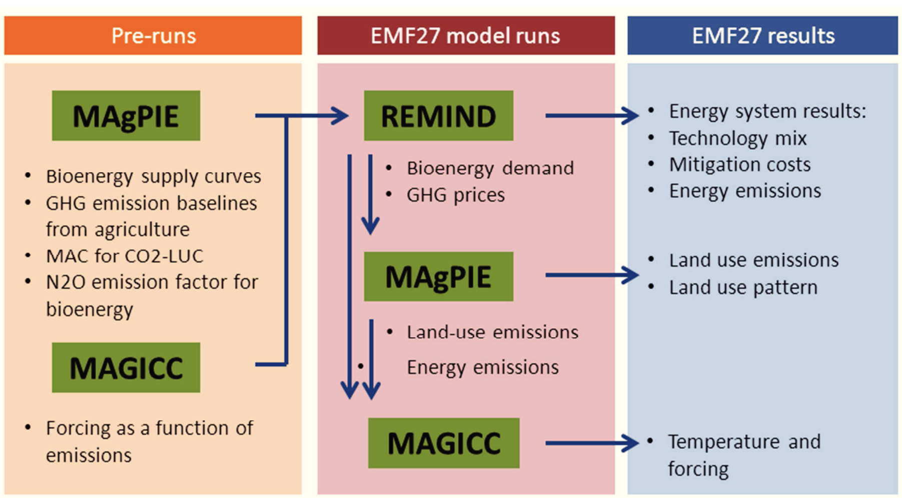


Figure S4: ***Data flow and interaction between the models used for the EMF27 scenario analysis.***

Forcing is calculated using the climate model MAGICC 6 (Meinshausen 2011).

2 Detailed results

2.1 Energy mixes

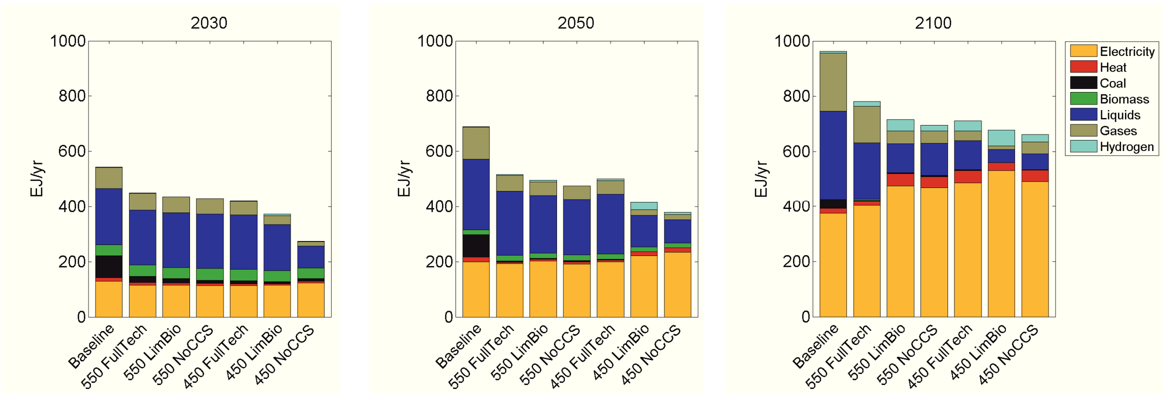


Figure S5: ***Final energy mixes across scenarios and time***

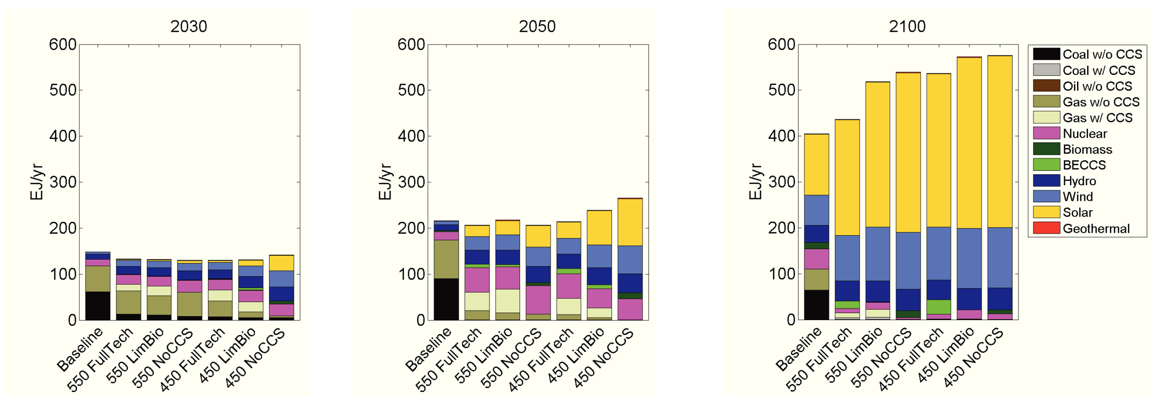


Figure S6: ***Secondary energy mixes in the power sector across scenarios and time***

Similar to gas with CCS, nuclear energy is a mid-term mitigation option with maximum deployment levels around 2050. The resource potential of 23 Mt of uranium (NEA 2010) is exhausted in all scenarios[1]. Climate policy stringency and technology availability mainly affect the temporal distribution of deployment. Studies that consider nuclear power to be unlimited, suggest higher contributions of nuclear power to emission mitigation (Mori 2012, Luckow 2010).

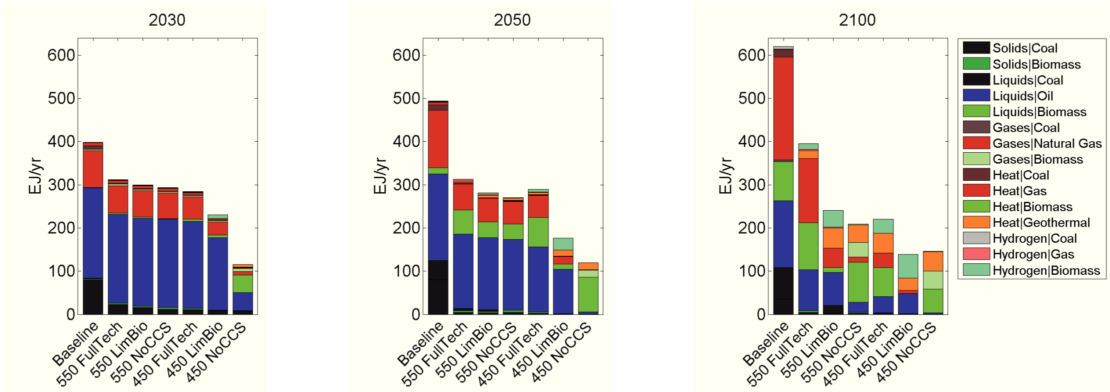


Figure S7: ***Secondary energy mixes in the non-electric sector across scenarios and time***

2.2 Forcing targets and resulting emission budgets in ReMIND

The forcing targets imposed in ReMIND include the following forcing agents: CO_2, CH4, N2O, F-Gases, Montreal Gases, SO2, black and organic carbon (including BC on snow), aerosols from biomass burning, stratospheric and tropospheric ozone, stratospheric water vapor from methane oxidation and indirect aerosol forcing. Though negative forcing e.g. from sulfur emissions is accounted for, it cannot be used by the model to control the total forcing level. The EMF27 forcing targets refer to the so called AN3A forcing (Kriegler et al., this issue) that does not include forcings from nitrate, mineral dust, and land-use albedo. The temperature calculations are based on the total forcing and result in 1.6°C and 2.0°C in 2100, respectively, when assuming a climate sensitivity of 3 °C.

The non-Kyoto forcings nearly cancel each other when the targets are reached, so that the Kyoto forcing is similar to the AN3A forcing. CH_4 and N_2O account for 0.7-0.8 W/m^2, which leaves a CO_2 forcing target of 1.9 respectively 2.7 W/m^2. This defines a CO_2 budget for the period 2005-2100. From this total CO_2 budget, the CO_2 land use emissions have to be subtracted, which yields the budgets for CO_2 fossil fuels and industry. Budgets that have been assessed to be compatible with 450 ppm vary widely. Meinshausen et al. (2009) calculated, that with a carbon budget of 886 Gt CO_2 (including carbon emissions from land use change) from 2000-2049, the chance of exceeding 2°C is 20%. The RCP 3PD scenario (v. Vuuren et al. 2007), which is also compatible with 450 ppm, arrives at a CO_2 budget of about 1400 Gt CO_2 for the same time horizon. Reasons for this variation are among others uncertainties in the climate system and the carbon cycle. When we compare the carbon budget calculated with ReMIND with others, we find that it is at the lower end.

Table S6: ***Forcing targets and emission budgets (2005-2100) for the two climate policy cases.***

	450 ppm	550 ppm	Unit
AN3A forcing	2.8	3.7	W/m^2
Kyoto forcing	2.8	3.5	W/m^2
Total forcing	2.5	3.3	W/ m^2
CO_2 forcing	1.9	2.7	W/m^2
CO_2 budget (total)	807-920	1670-1780	Gt CO_2
CO_2 budget (Fossil fuel and Industry)	723-845	1600-1700	Gt CO_2

2.3 Contribution of BECCS to GHG emission mitigation

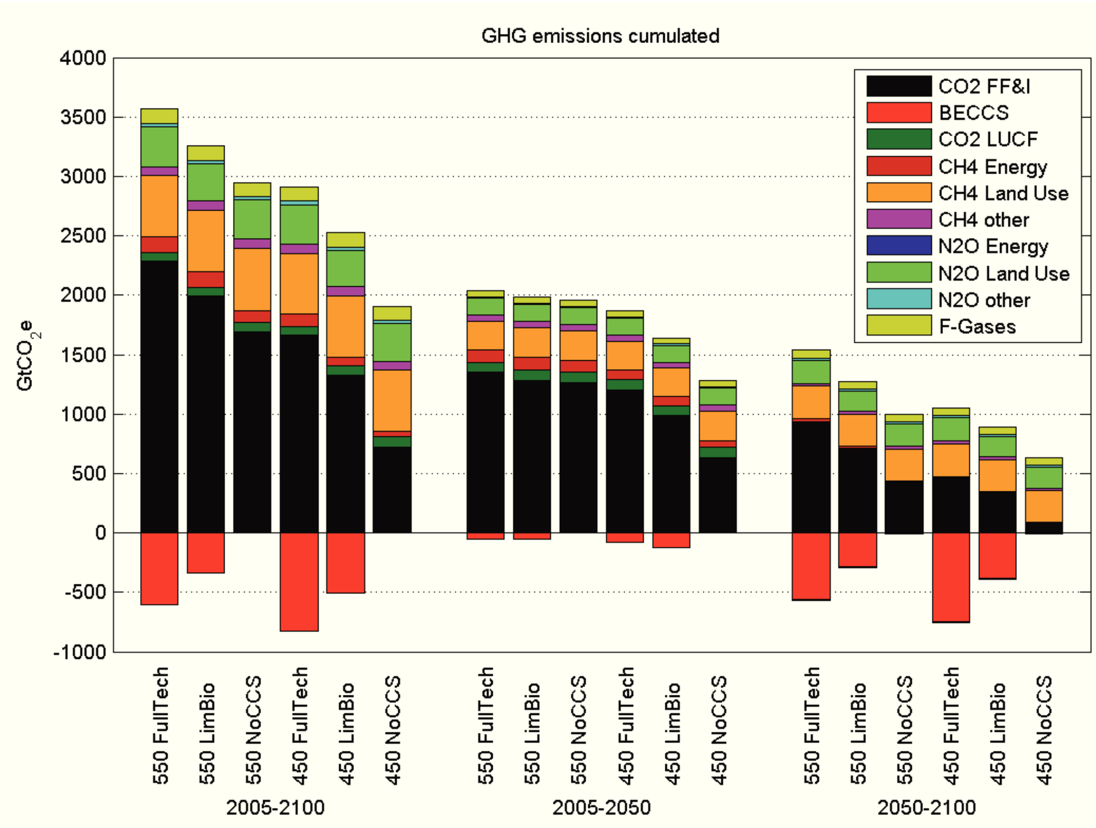


Figure S8: ***Global GHG emissions [GtCO$_2$_eq] including negative emissions cumulated over different time periods across all policy scenarios.***

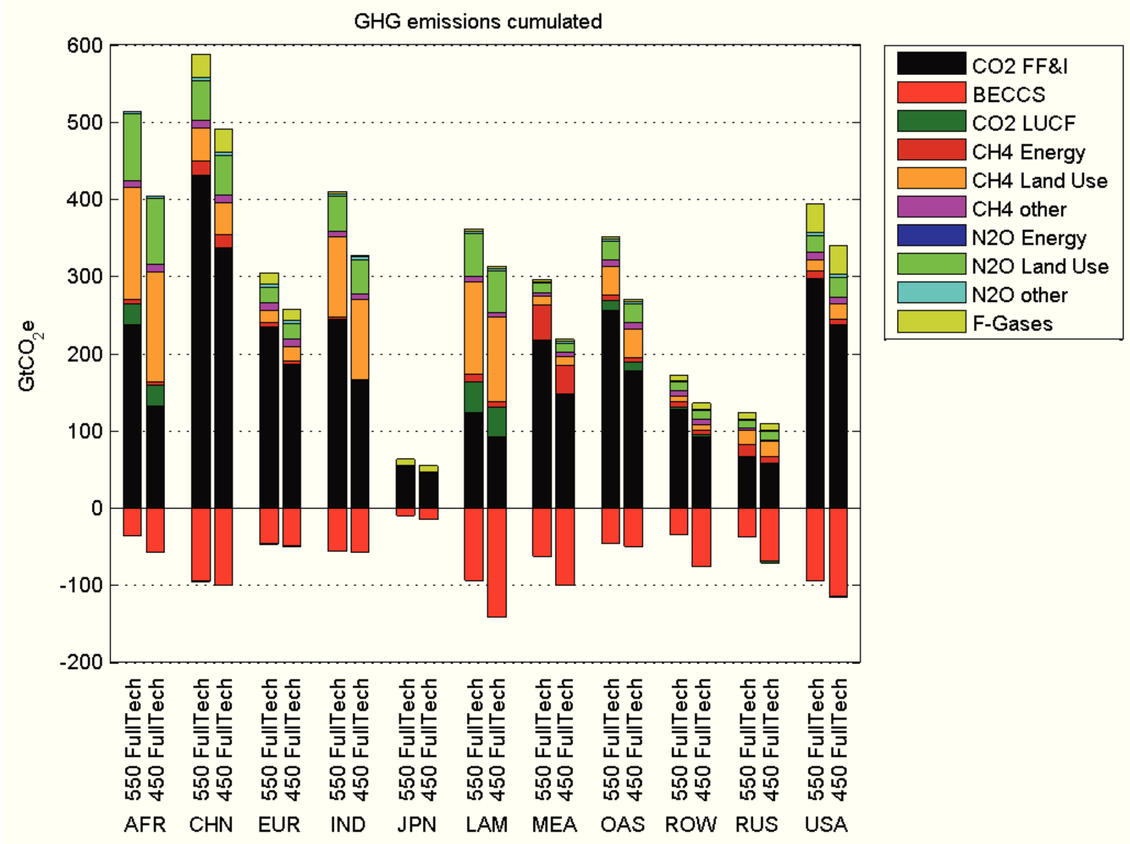
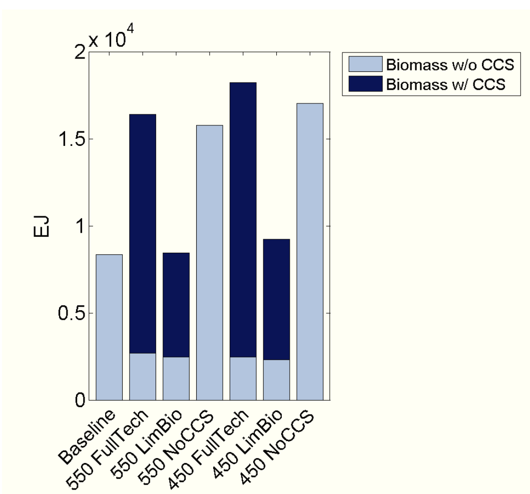


Figure S9: ***Regional GHG emissions [GtCO$_2$_eq] including negative emissions cumulated from 2005-2100 across the two FullTech scenarios.***

2.4 Captured carbon



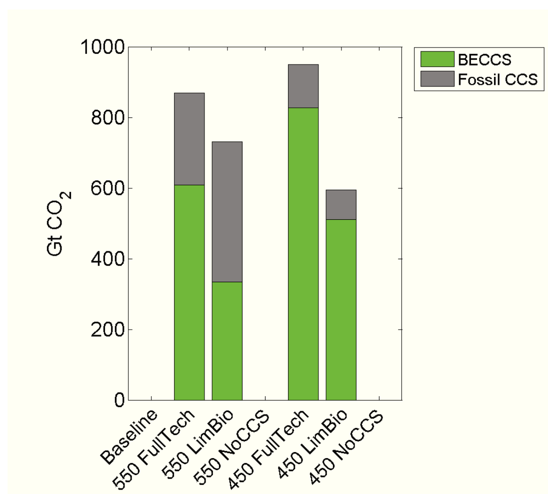


Figure S10: *Bioenergy and CCS: Left: Primary bioenergy deployed with and without CCS cumulated (2005-2100), Right: Captured carbon from bioenergy and fossil fuels cumulated (2005-2100)*

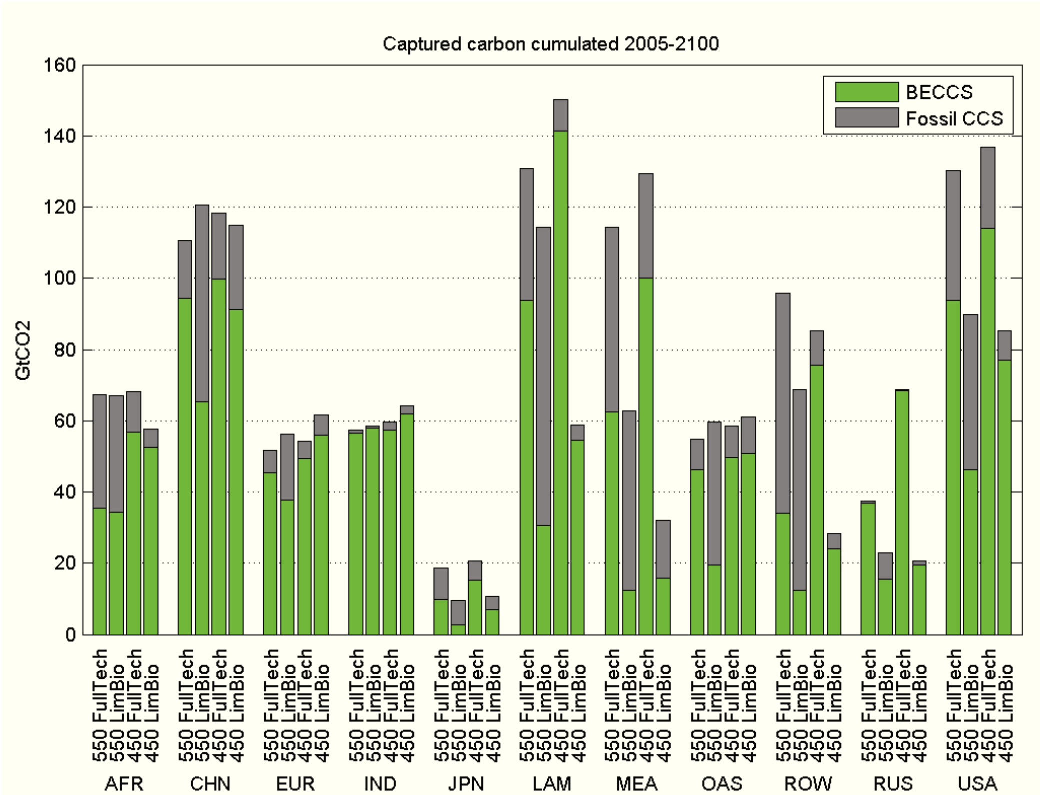


Figure S11: *Captured carbon from 2005-2100 for scenarios with CCS available (see also* Figure S10*)*

2.5 Regional energy prices for liquids

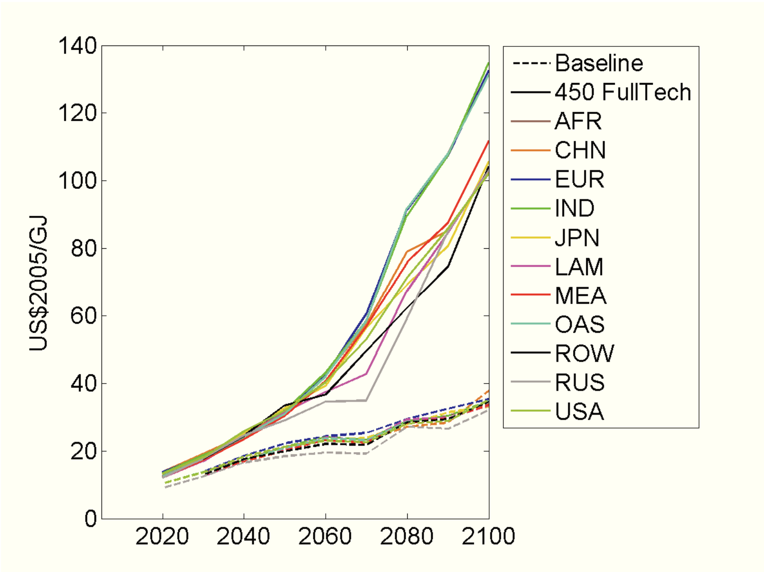


Figure S12: Prices for liquid fuels across regions and two scenarios.

2.6 Regional revenues from bioenergy

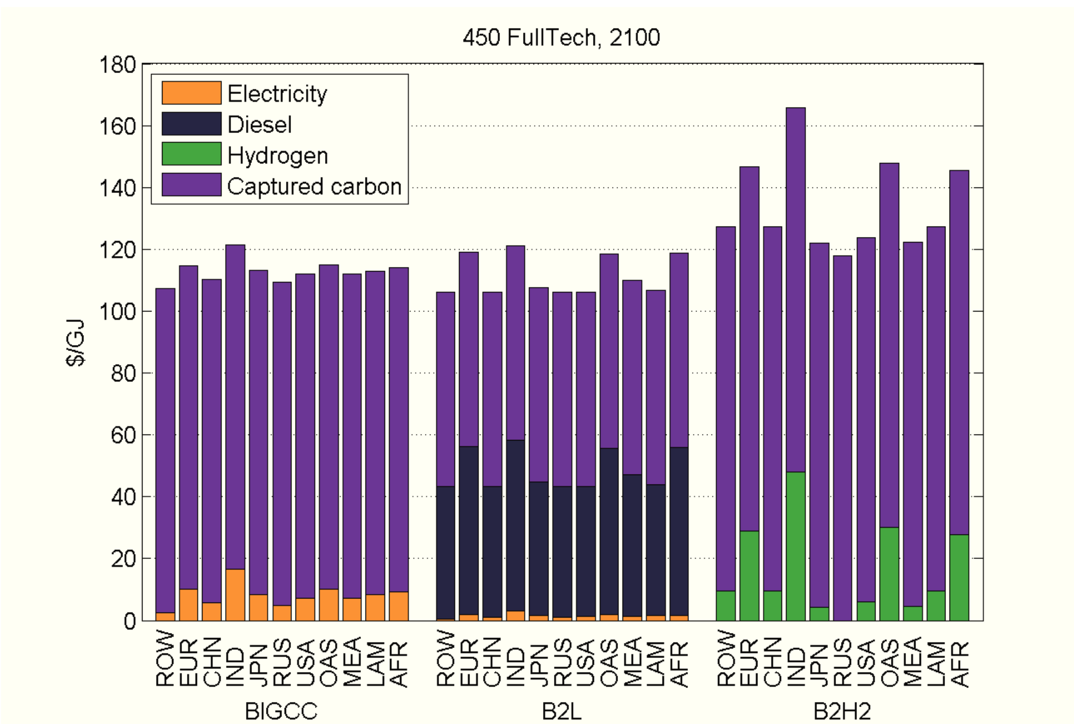


Figure S13: *Value of energy versus value of carbon. Revenues from production of electricity, diesel, hydrogen, and negative emissions in 2100 across regions for the 450 FullTech scenario.*

2.7 Agricultural production costs

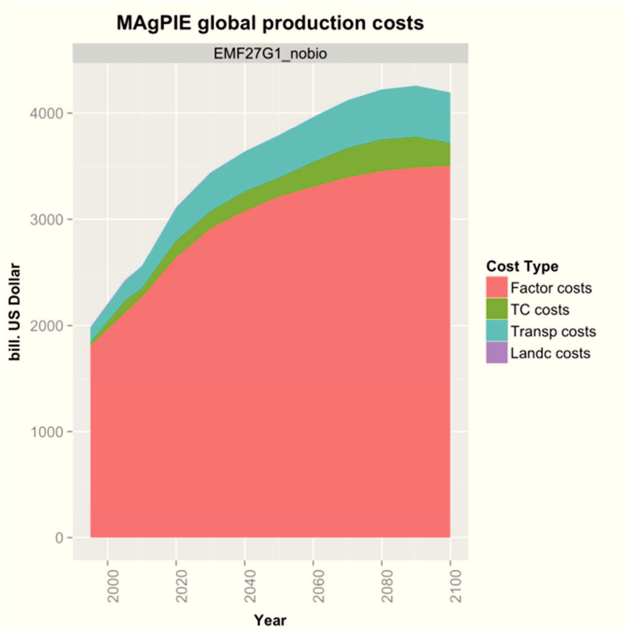


Figure S14: *Components of agricultural production cost for the Baseline scenario.*

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Chapter 6

Can air pollutant controls change global warming?*

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Can air pollutant controls change global warming?

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ABSTRACT

In this paper we analyze the interaction between climate and air pollution policies using the integrated assessment model REMIND coupled to the reduced-form climate model MAGICC. Since overall, aerosols tend to cool the atmosphere, there is a concern that a reduction of pollutant emissions could accelerate global warming and offset the climate benefits of carbon dioxide emission reductions.

We investigate scenarios which independently reduce emissions from either large-scale sources, such as power plants, or small-scale sources, such as cooking and heating stoves. Large-scale sources are likely to be easier to control, but their aerosol emissions are characterized by a relatively high sulfur content, which tends to result in atmospheric cooling. Pollution from small-scale sources, by contrast, is characterized by a high share of carbonaceous aerosol, which is an important contributor to global warming.

We find that air pollution policies can significantly reduce aerosol emissions when no climate policies are in place. Stringent climate policies lead to a large reduction of fossil fuel use, and therefore result in a concurrent reduction of air pollutant emissions. These reductions partly reduce aerosol masking, thus initially counteracting the reduction of greenhouse gas forcing, however not overcompensating it. If climate policies are in place, air pollution policies have almost no impacts on medium- and long-term radiative forcing. Therefore there is no conflict of objectives between clean air and limiting global warming. We find that the stringency of air pollution policies may influence the rate of global temperature change in the first decade. Afterwards climate change mitigation policies are of greater importance.

1. Introduction

In the fourth assessment report of the IPCC (Forster et al., 2007), radiative forcing (RF) from direct and indirect aerosols was estimated to be $-1.2\ \mathrm{Wm^{-2}}$. Total anthropogenic RF was estimated to be $1.6\ \mathrm{Wm^{-2}}$. This means that in 2005 aerosol forcing masked almost half of the total positive anthropogenic RF. The fifth assessment report (Myhre et al., 2013) introduced the concept of efficient radiative forcing (ERF), which accounts for perturbations of surface and tropospheric conditions. In this concept, total anthropogenic ERF and total aerosol ERF are estimated to be 2.3 and $-0.9\ \mathrm{Wm^{-2}}$, respectively.

Different aerosol species have different atmospheric properties. Sulfur dioxide emissions form sulfate aerosols, which have a cooling effect. Organic carbon (OC) also has a cooling effect, whereas black carbon (BC), commonly known as soot, leads to warming. According to the last IPCC report (Myhre et al., 2013) BC is one of the major contributors to present day radiative forcing after CO_2 and CH_4. All aerosols

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1462-9011/

have a short lifetime of days or weeks in the atmosphere. Thus, aerosol emission reduction could almost immediately influence the radiative forcing balance, leading to either warming or cooling depending on the type of aerosol that is reduced.

Around 75% of anthropogenic sulfur emissions (Smith et al., 2001) and more than half of BC emissions (Bond et al., 2004) arise in the combustion process of fossil fuels. In order to effectively control climate change, the energy system has to undergo a transformation leading to substantial reductions of CO_2 emissions. To achieve this transformation, fossil fuel use has to be reduced. Thus, when CO_2 emissions are reduced, aerosol emissions are necessarily reduced at the same time. In addition, air pollution policies are already being implemented to further reduce aerosol emissions due to health concerns. Both policies reduce aerosol emissions independently. In this study, we investigate the interplay between them.

It is already well understood that climate change mitigation policies substantially decrease air pollution (Bollen et al., 2010; Van Vliet et al., 2012; McCollum et al., 2013). The impact of air pollution policies on the climate on the other hand is less clear. Ramanathan and Feng (2008) argued that a quick removal of sulfate aerosols from the atmosphere may result in accelerated global warming. Kopp and Mauzerall (2010) state that the 2 °C target may become economically unachievable if SO_2 is reduced and BC is not. These studies suggest that there may be a conflict of objectives between air pollution policies and climate policies.

Air pollution policies focusing mainly on BC on the other hand could be climatically favorable. A number of publications have already proposed to reduce BC emissions to slow global warming (Hansen et al., 2000; Schellnhuber, 2008; Jacobson, 2010). Bollen et al. (2009) applied a cost-benefit approach and reached lower temperatures with air pollution policies than without. In their approach they focused on particulate matter only, not taking into account the cooling effects of sulfur. Two recent assessments of UNEP suggested that measures to control BC, methane and tropospheric ozone could reduce global warming by 0.4 °C (UNEP, 2011) respectively 0.5 °C (UNEP/WMO, 2011) by 2040. Shindell et al. (2012) reported a reduction of 0.5 °C by 2050, 0.2 of which could be attributed to BC. The remaining 0.3 °C is largely due to methane reductions.

Current air pollution policies have already successfully reduced sulfur and particulate matter emissions from the industry and power sector e.g. in the United States, Western Europe and Japan. In the residential sector, particulate matter emissions continue to rise in China, India, and other south-eastern Asian countries. Reducing aerosol emissions in this sector would not only reduce air pollution and indoor smoke which is thought to cause millions of premature deaths (Rao et al., 2012), but would also be favorable from a climate perspective.

In this study, we analyze the effects of aerosol emissions on climate in a detailed modeling framework of the energy–economy–climate system including a full suite of emissions. This framework takes not only the interaction between CO_2 emissions reduction due to climate policies and concurrent aerosol emissions reduction into account, but also the interdependence of different aerosol species.

An early attempt to quantify aerosol forcing was undertaken in the representative concentration pathways (RCP) framework, a set of scenarios reaching different radiative forcing levels in 2100 (Van Vuuren et al., 2011). They found a general declining trend in aerosol emissions, with more stringent climate policies leading to even lower emissions. Co-benefits for air pollution policies from climate policies have been confirmed by a number of studies (Bollen et al., 2010; Riahi et al., 2012; Van Vliet et al., 2012; McCollum et al., 2013). The analyses of integrated assessment scenarios presented by Rose et al. (2013) and Smith and Bond (2013) found a continuous decline in aerosol forcing over the course of this century, thus playing a minor role in 2100. The impact on climate change in the short and medium term is less clear. With this paper, we aim to illuminate how climate change is affected by various air pollution emission scenarios over the course of this century. To this end we use the integrated assessment model REMIND coupled to the reduced form climate model MAGICC. REMIND has a detailed energy system representation with emissions calculated technology-specific from fuel consumption and emission control measures. As a second aspect we analyze the offset of greenhouse gas forcing reductions due to simultaneous aerosol masking reductions. A third novelty of this paper is that we apply different settings of air pollution policies, targeting either large-scale sources, such as power plants, or small-scale sources, such as cooking and heating stoves. This implies a focus on sulfur when targeting large-scale sources and a focus on BC when targeting small-scale sources. We analyze the impact of these different air pollution policies on emission levels, forcing targets and temperature and rate of temperature change.

This paper is structured as follows. In Chapter 2 we describe our methodological approach and outline the scenarios. We present our results in Chapter 3, starting with an analysis of BC and SO_2 emissions. Section 3.2 studies the effects of air pollution scenarios on radiative forcing. These effects are explored in more depth in Section 3.3, where we analyze the offset of Kyoto forcing reductions by aerosol forcing. In Section 3.4 we study differences in temperature and rate of temperature change. Finally, we summarize and discuss our results in Section 4.

2. Methodology

2.1. *The REMIND Model*

For our analysis, we use the multi-regional integrated assessment model REMIND (Leimbach et al., 2010; Bauer et al., 2012; Luderer et al., 2013b). Each single region is modeled as a hybrid energy–economy system and is able to interact with the other regions by means of trade. Tradable goods are the exhaustible primary energy carriers coal, oil, gas and uranium, a composite good, and emission permits.

The economy is modeled by a Ramsey-type growth model which maximizes utility, a function of consumption. Labor, capital and end-use energy generate the macroeconomic output, i.e. GDP. The produced GDP covers the costs of the energy system, the macroeconomic investments, the export of a composite good and consumption.

The energy sector is described with high technological detail. It uses exhaustible and renewable primary energy carriers and converts them to final energies as electricity, heat and fuels. Various conversion technologies are available, including technologies with carbon capture and storage (CCS). A detailed documentation of the REMIND model is provided by Luderer et al. (2013a).

The emissions associated with the technologies are transferred to the reduced complexity coupled climate-carbon cycle model MAGICC6 (Meinshausen et al., 2011a) which calculates forcing and temperature. We use a default and a probabilistic version. The default version uses parameter settings as described in Meinshausen et al. (2011b), where they were developed for the calculation of the default RCP concentration trajectories. The probabilistic version uses joint distributions of parameter distributions derived from a historical constraint, see supplementary material (Meinshausen et al., 2009).

For climate protection targets we use a Kyoto-gas budget of 550 Gt Ceq for the time range from 2005 to 2100, which results in our modeling framework in a best-estimate total forcing of all anthropogenic sources of approximately 2.5 Wm^{-2} in 2100. This forcing target is consistent with the RCP 2.6 scenario (Van Vuuren et al., 2007) and the 450 ppm scenario of the EMF27 study (Kriegler et al., 2013). The climate target is set as a multi-gas budget where we take the long-lived Kyoto gases CO_2, N_2O and CH_4 into account.[2] The emissions of each year of the time horizon (2005–2100) are converted to CO_2 equivalents and added up. This approach ensures that the forcing from long-lived greenhouse gases is essentially equal, such that differences in the climate outcomes can be attributed to the effects of air pollutant forcing.

2.2. *Aerosol emissions from the energy system*

In 2005, total global anthropogenic sulfur emissions amounted to 58.1 Tg S, with 67% coming from fossil fuel combustion in the energy system and industry, 17% from residential and transportation sectors, 13% from industrial processes, and 3% from land-use and land-use change (EDGAR, 2011). Coal and crude oil usually contain 1–2% sulfur by weight. About half of the global sulfur emissions arise from coal combustion and another 25% from oil combustion (Smith et al., 2001). The most important sources of BC emissions are open burning (about 42%) and contained combustion of coal, biofuel, and transportation fuels (Bond et al., 2004). Sulfur emissions in REMIND are calculated using time-dependent, region- and technology-specific emission factors for all technologies using coal and oil. BC and OC emissions are calculated the same way, including emissions from biofuels.

Exposure to high levels of SO_2 can cause respiratory problems, chronic bronchitis, heart diseases and exacerbate existing asthma (Anderson et al., 1997; Sunyer et al., 1997; Hedley et al., 2002). High levels of indoor smoke can cause heart and lung diseases and are held responsible for millions of premature deaths in developing countries (Rao et al., 2012). Because of these negative impacts, governments have intervened to decrease sulfur and fine particulate matter emissions.

There are two ways of reducing aerosol emissions: activity independent reductions, e.g. the implementation of scrubbers, which lower the emission factors, and activity reductions, i.e. the reduction of sulfur- and soot-intensive technologies, respectively. This can be achieved e.g. in the case of sulfur by shifting to conversion technologies with lower specific SO_2 emissions, like IGCC (integrated gasification combined cycle) power plants instead of conventional pulverized coal power plants for the conversion of coal to electricity, or by reducing the demand for coal.

In the past decades, emission reduction measures have been put into place. Sulfur removal during petroleum refining reduced the sulfur content in crude petroleum by approximately 40% by the end of the 1990s (Smith et al., 2004). The United States, Canada, western Europe and Japan already implemented sulfur emission controls of 50–90% (Smith et al., 2005). There has also been a shift to less sulfur-intensive fuels such as natural gas.

High and rising pollution rates are now observed especially in the fast developing east and central Asian countries (Forster et al., 2007; EDGAR, 2011). Due to the negative health impacts, these countries are expected to reduce their aerosol emissions and implement emission reduction measures. Therefore in our implementation emission factors are assumed to decline with increasing affluence. The rate of decline is particularly fast for middle income countries with fast economic growth. A detailed description of the development of emission factors can be found in the supplementary material S1.

Air pollutant abatement costs are calculated on a technology level (see supplementary material S3), and affect the competitiveness of technologies. While activity levels, i.e. technology choice and deployment are endogenous model results, the emission factors of specific technologies are exogenous assumptions subject to the methodology described in the supplementary material S1 and to the air pollution scenarios described in the following.

2.3. *Scenario description*

Large emitters, such as power stations or steel plants have emission signatures that are distinctly different from those of small scale sources, such as residential heating and cooking stoves, or transportation. In this paper, we therefore account for the different possibilities to apply air pollution policies by dividing technologies into large- and small-scale sources, to which different stringencies of air pollution policies are applied independently. Large-scale sources comprise the energy and industrial sector. Small scale sources are residential energy use and transportation.

Since large-scale sources are more concentrated and smaller in number, air pollution policies targeting them might be easier to implement. Small-scale sources, by contrast, are more heterogeneous and much larger in number (e.g. cooking stoves or individual vehicles (Mainali et al., 2012)), which might make them harder to access. At the same time, due to

[2] N_2O and CH_4 are converted to CO_2 equivalents using the 100 year global warming potentials given in the AR4, i.e. 1 kg CH_4 is equivalent to 25 kg CO_2 and 1 kg of N_2O is equivalent to 298 kg CO_2. F-gases are exogenous in the model and are therefore not included in the target.

Table 1 – Setup of air pollution policy scenarios targeting different sources.

		Additional air pollution policies targeting small-scale sources (residential, transport)			
		None	**Weak**	**Medium**	**Stringent**
Additional air pollution policies targeting large-scale sources (power sector and industry)	**None**	CNTF			
	Weak		WEAK		SMALL
	Medium			STD	
	Stringent		LARGE		STRGT

different emission characteristics of large- and small-scale sources, we expect the scenarios to have a distinct impact on emissions of various aerosol species. This may have an effect on the climate outcome, as discussed in Sections 3.3 and 3.4.

We use the REMIND model to run six different air pollutant emission scenarios, which can be interpreted as different stringencies of air pollution policies. The scenarios differ in the stringency of policies applied to small-scale and large-scale sources (Table 1):

1. STD: A standard case
2. WEAK: Weak air pollution policies in all sectors
3. STRGT: Stringent air pollution policies in all sectors
4. LARGE: Stringent air pollution policies on large-scale sources, weak air pollution policies on small-scale sources
5. SMALL: Stringent air pollution policies on small-scale sources, weak air pollution policies on large-scale sources
6. CNTF: A counterfactual: no air pollution policy case with aerosol emission factors remaining constant at their 2005 levels

The STD case applies medium air pollution policies on all sources. The WEAK case applies only weak air pollution policies for all sources. Emission factors are assumed to decrease later than in the standard case, which is equivalent to a later enforcement of possible measures to reduce air pollution. In the STRGT case, emission factors decrease earlier than in the standard case, accounting for an earlier application of air pollution control technologies. When targeting only large-scale (small-scale) sources, the same emission factor trajectories as in the STRGT case are applied for technologies associated with these large-scale (small-scale) sources, whereas the WEAK case emission factors are applied for all others. In a hypothetical additional scenario we freeze the emission factors of all aerosols to their 2005 values (counterfactual CNTF). This case is to show the effects of aerosol emissions on the climate system and the total amount of emissions if emission factors remained as they are today.

These six scenarios are analyzed in a baseline case (BASE) and in a case with additional climate policies (POL), formulated as a Kyoto-gas budget of 550 Gt Ceq for the time range from 2005 to 2100 as described in Section 2.1, resulting in a total of twelve scenarios considered.

3. Results

3.1. BC and SO_2 emissions

In this section we look at the impacts of climate and air pollution policies on air pollutant emissions. In the base year (2005) calibration of REMIND, 39.8% of global sulfur emissions come from the power sector, 23.3% from fossil fuel combustion in the industry, 12.9% from the transport sector, 10.0% from the residential sector, and 14.0% from industry process emissions and open burning. As 63% of global anthropogenic SO_2 is emitted from large-scale sources and 23% from small-scale sources, air pollution policies targeting the power sector and industry (LARGE and STRGT scenarios) lead to faster decreasing SO_2 emissions. Fig. 1 shows global SO_2 emissions by sector in BASE (a) and POL (b) scenarios in 2030. In the LARGE and STRGT scenarios, emissions from power plants decrease substantially. In BASE scenarios this leads to a total reduction as compared to the STD case. In POL scenarios, only the STRGT scenario achieves noteworthy reductions.

Fig. 2a shows the trajectories of SO_2 emissions. In the standard BASE case, sulfur emissions decrease from 115 Tg SO_2 in 2005 to 30 Tg SO_2 in 2100. In the SMALL and WEAK scenarios we observe a qualitatively different behavior. SO_2 emissions start to increase first, driven by an increased demand for fossil fuels, and remain above today's level until around 2050–2060. In the CNTF, emissions peak in 2050 at more than 220 Tg SO_2, which is a 100% increase relative to 2005 emissions, and remain far above today's level throughout the century. Due to potentially massive air quality and health impacts, such an extreme emissions increase is very unlikely to materialize.

Because of the reduction of fossil fuel use in the climate policy cases, SO_2 emissions are already much reduced in comparison to the baseline. Consequently air pollution policies have much less impact on the reduction of SO_2 emissions in POL than in BASE. With climate policies in place, we observe a temporary increase in SO_2 emissions only in CNTF. Even under low air pollution policies, emissions decline immediately. In POL STD, SO_2 emissions fall below all of the BASE cases in 2030. This means that within two decades climate policies reduce SO_2 emissions to lower levels than any of the modeled air pollution policies. This result supports the findings of other studies, e.g. (Bollen et al., 2010; McCollum

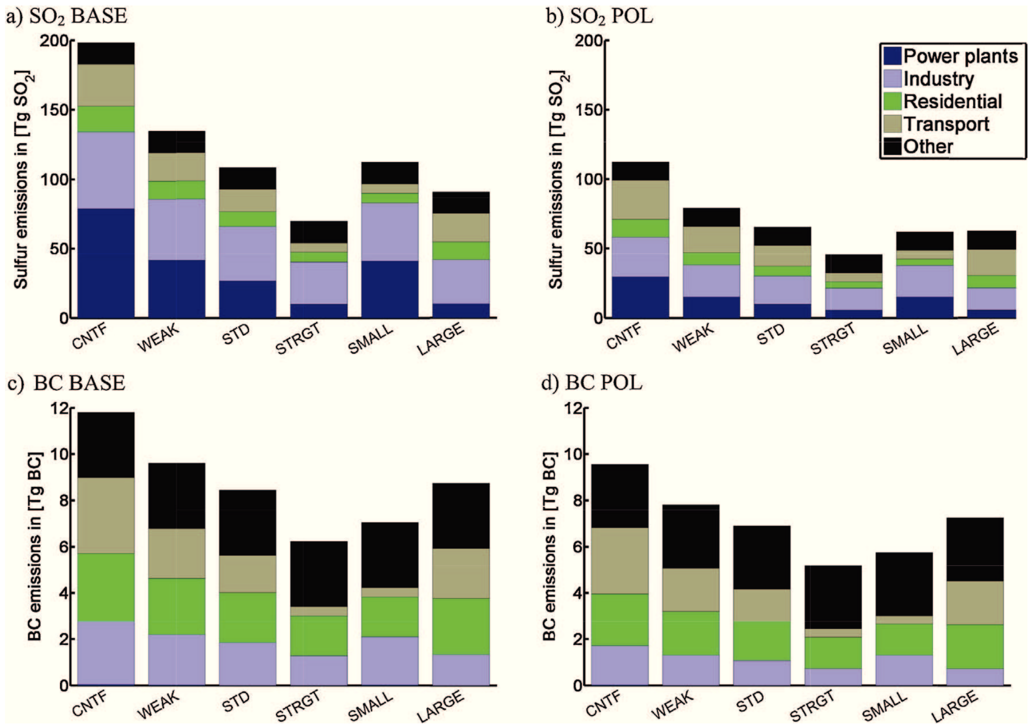

Fig. 1 – Global SO_2 (upper panel) and BC (lower panel) emissions by sector in 2030. The left panel shows scenarios without climate policies (BASE), the right panel with climate policies (POL).

et al., 2011; Van Vliet et al., 2012), who found that climate policies have considerable co-benefits for health.

For BC the picture is different. The largest share of emissions in the energy system arises in the residential and transport sector. Therefore STRGT and SMALL scenarios reduce BC emissions in 2030 visibly as compared to the STD case regardless of climate policies (Fig. 1c and d). In BASE STD, BC emissions decline from 8.8 Tg in 2010 to 4.5 Tg in 2100 (Fig. 2b). With STRGT air pollution policies, emissions decline faster and are around 1–2 Tg lower than the STD case until the middle of the century. The short-term reductions are in good agreement with Cofala et al. (2007), who estimated a reduction of energy system emissions from about 5.5 Tg BC in 2000 to under 4.5 Tg BC in 2030 if current legislation was applied, and to below 3 Tg BC if all technically possible reductions were applied. In the WEAK case, emissions increase first and remain around 1–2 Tg higher than the STD case for most of the century.

In the POL cases, fossil fuel use in the industry and power sector is already decreased. Therefore additional air pollution policies on these sources have less effect than in the BASE case. The residential and transportation sectors are more difficult to decarbonize and are therefore much more sensitive to air pollution policies. Targeting small scale sources noticeably reduces BC emissions in the first half of the century, even with climate policies already in place.

There is considerable uncertainty about historic emission levels. For sulfur, uncertainty in global emissions is estimated

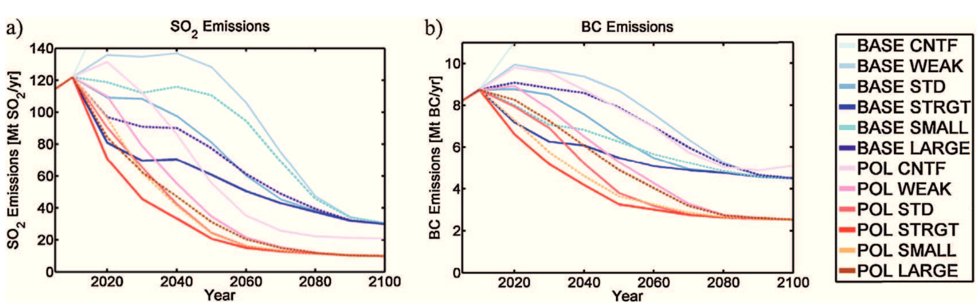

Fig. 2 – Total (a) SO_2 and (b) BC emissions in baseline (blue lines) and climate policy (red lines) cases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

to be roughly 10% (Smith et al., 2011). Bond et al. (2013) estimate the 90% confidence interval for energy-related emissions in 2000 to be 1.2–15 Tg BC. Moreover, the pathways of aerosol emissions depend on assumptions in modeling. A sensitivity study on different parameter values for the maximal level of emission control can be found in the supplementary material S4. Though the exact timing of emission reductions and their absolute value are uncertain, substantial co-benefits for health from climate policies remain as a robust insight.

3.2. *Effect on radiative forcing*

The changes in aerosol emissions discussed in the previous section translate into changes in radiative forcing. Fig. 3 shows aerosol forcing components for BASE STD (a), POL STD (b) and the difference of the two (c). Since climate policies are set up as a Kyoto gas emission budget, Kyoto forcing does not differ across POL cases. Differences in total forcing are determined by differences in aerosol forcing. The biggest differences occur in the first decades. From 2050 on, the difference in SO_2 direct and cloud indirect forcing within the POL cases is less than 0.1 Wm^{-2}, with the exception of the CNTF (Fig. 3d).

The difference in BC and OC forcing is even less and also points in the opposite direction, thus offsetting part of the difference in SO_2 forcing. Therefore total forcing differs only in the first decades and afterwards converges between the different POL cases. Since in 450 ppm scenarios the total forcing usually peaks around the middle of the century (Van Vuuren et al., 2007), the choice of air pollution policies has only little effect on the maximal forcing and even less on the forcing in 2100. Even the CNTF lowers neither the peak in the total forcing noticeably nor the forcing in 2100 as compared to STD (Fig. 4d). Therefore we conclude that the air pollution policy regime has a negligible effect on the achievability of long-term climate protection targets.

In the BASE cases we see larger differences in the SO_2 forcing. The WEAK scenario shows up to 0.2 Wm^{-2} lower SO_2 forcing than the STRGT scenario in the first half of the century, corresponding to the higher emissions discussed in the previous section. In the CNTF, SO_2 forcing decreases until 2050, leading to an increasing difference to the other BASE cases up to around 0.4 Wm^{-2} in 2100. However, this quite noticeable lower SO_2 forcing comes at the expense of extremely high pollutant emissions which are unlikely to materialize, as the impacts on health and air quality would likely be quite dramatic.

Like emissions, aerosol forcing is uncertain. The uncertainty in the climate system is shown in supplementary material S5. Due to the projected decrease in aerosol emissions, absolute forcing levels and therefore uncertainty decreases over time. Yet long-term forcing differences due to different air pollution policies are still in the range of uncertainty. This confirms our conclusion that air pollution policies have only a negligible effect on the achievability of long-term climate protection.

3.3. *Offset of Kyoto forcing reductions by aerosol forcing reductions*

When climate policies are applied, Kyoto gas emissions as well as associated aerosol emissions are reduced compared to the

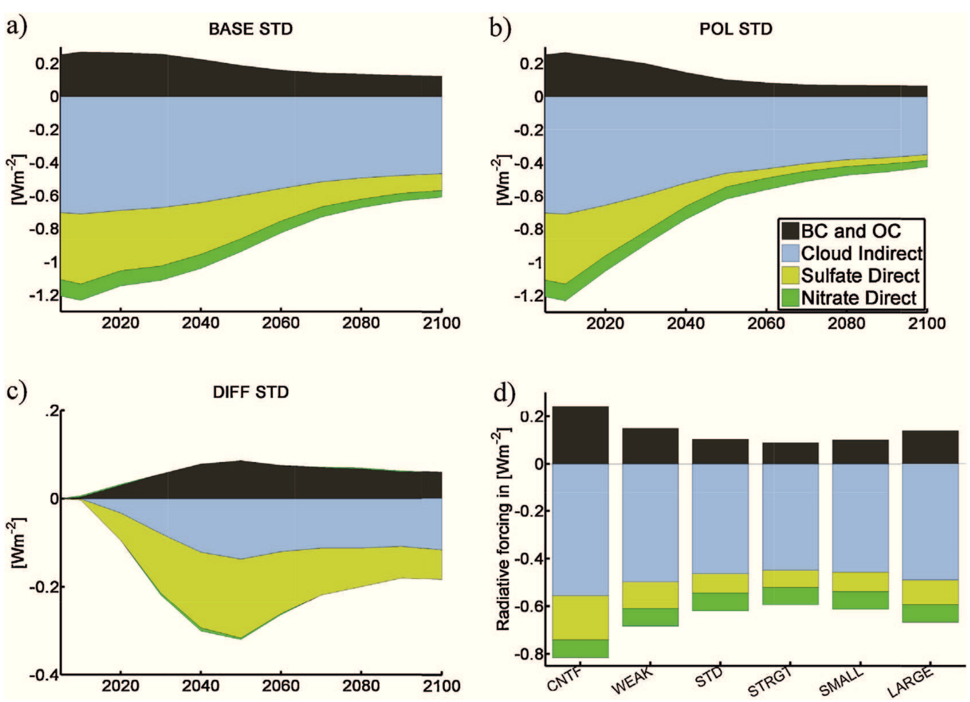

Fig. 3 – Aerosol forcing components in (a) BASE STD, (b) POL STD and (c) difference between BASE STD and POL STD. Panel (d) shows aerosol forcing components in 2050 in all POL scenarios.

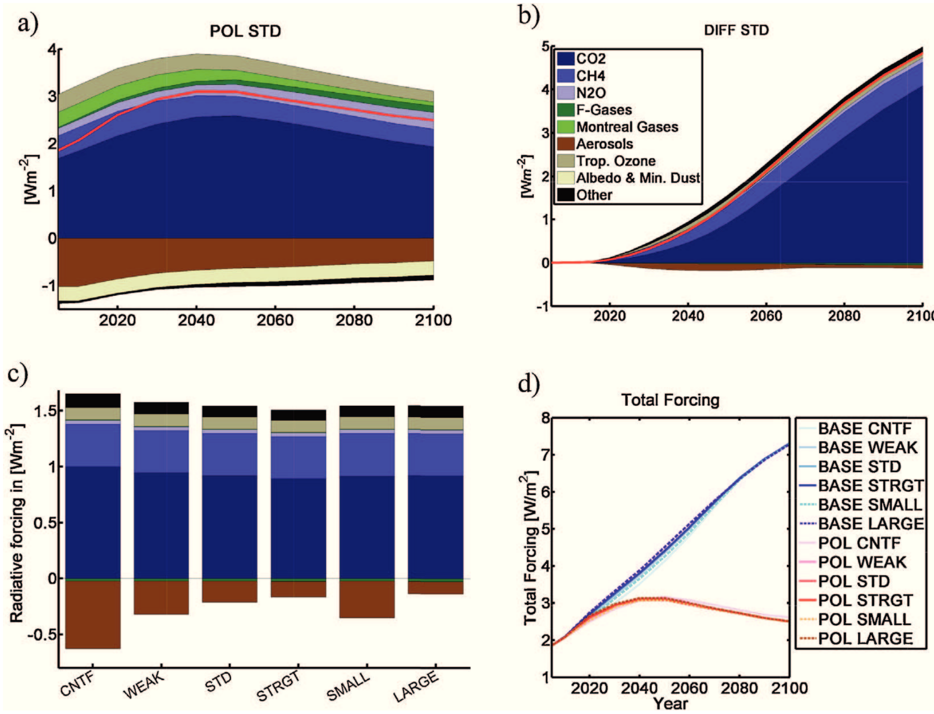

Fig. 4 – Forcing components for (a) POL STD and (b) difference between BASE STD and POL STD. The lowest positive area (dark blue) represents the CO_2 forcing, above CH_4 (medium blue), N_2O (light blue), F-gases (dark green), Montreal gases (light green) and other components (gray and black). The negative area (brown) shows the forcing from SO_2, BC, OC, and indirect aerosol forcing. The red line indicates total forcing. Panel (c) shows the forcing difference ΔRF between BASE and POL for all scenarios in 2050. Aerosol forcing is negative, therefore the difference is negative, too. Panel (d) shows the total forcing for all BASE and POL cases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

baseline from 2010 on. This leads to a reduction of the Kyoto gas and aerosol forcing. Fig. 4a shows the contribution of the most important forcing agents CO_2, CH_4, N_2O, aerosols, F-gases, Montreal gases, Tropospheric Ozone, albedo and mineral dust, and the residual to total forcing for the standard POL case. The difference between BASE and POL radiative forcing $\Delta RF = RF(BASE) - RF(POL)$ is illustrated for the same forcing agents in Fig. 4b. A positive number means that the BASE forcing is higher than the POL forcing. Since the aerosol forcing is negative, higher emissions lead to lower forcing in the BASE than in POL which shows up as a negative part in Fig. 4. The difference in total forcing is always positive, meaning that total POL forcing stays below total BASE forcing. Therefore temperature rise will be slower in the POL cases than in the BASE cases.

The negative aerosol forcing is sometimes referred to as a masking effect: It offsets the positive forcing from long-lived GHGs, however is only temporary since the lifetime of aerosols in the atmosphere is in the range of days (Forster et al., 2007). Reductions in aerosol emissions translate immediately into reductions in the forcing. This reduction of the negative aerosol forcing in the climate policy case cancels a fraction of the reduction of the Kyoto forcing. In the first years, this fraction is in the range of 50% in the standard case. In 2040, about a quarter of the reductions in Kyoto gas forcing are offset by reductions in aerosol forcing (see Fig. 4b). To compare the influence of different air pollution policies, we concentrate on the ratio of the reduction of aerosol forcing to the reduction of Kyoto gas forcing, i.e. $ratio = \Delta RF(aerosol)/\Delta RF(Kyoto)$. Fig. 5 shows this ratio for the different air pollution policy cases.

The variation in $\Delta RF(aerosol)$ within the cases with different stringency of air pollution policies arises mainly from the variation in the BASE cases. Air pollution policies lead to less aerosol emissions in the BASE cases and thus to less negative forcing. In the POL cases, the decreasing demand for fossil fuels already decreases aerosol emissions independently from air pollution policies, which leads to a smaller range of aerosol forcing within the POL cases. Therefore $\Delta RF(aerosol)$ decreases with increasing stringency of air pollution policies. As the variation in $\Delta RF(Kyoto)$ is, by design, negligible within the sets of BASE and POL cases, the same holds for the ratio.

This means that with stringent air pollution policies less reduction in Kyoto gas forcing is offset by reductions in aerosol forcing. Therefore the difference in temperature rise between BASE and POL is more pronounced in cases with stringent air pollution policies.

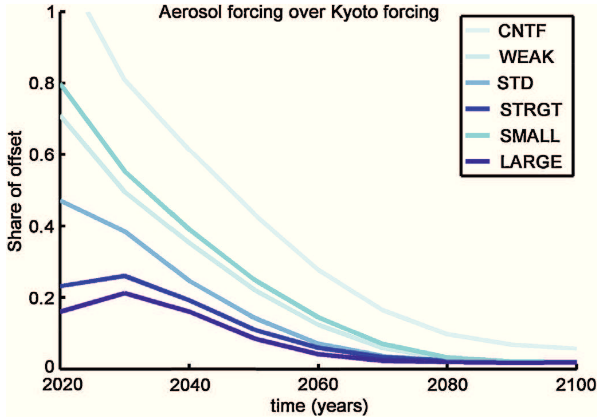

Fig. 5 – Ratio of BASE–POL difference in aerosol forcing to difference in Kyoto gas forcing. A ratio of one means that the difference of the positive forcing is canceled by the difference in aerosol forcing, such that total forcing of POL and BASE is equal. If the share is lower, then total forcing of BASE exceeds total forcing of POL. We compare the share of positive forcing being offset by aerosol forcing for the six different air pollution policies.

3.4. *Temperature and rate of temperature change*

A faster reduction of aerosol emissions through air pollution or climate policies would lead to a faster removal of the aerosol masking which may speed up global temperature change. As the aerosol forcing reacts within days or weeks to changes in emissions, this effect would be strongest in the first years after implementation of such policies. We have seen in Section 3.1 that by 2100 aerosol emissions are reduced to a similar level independently of air pollution policies. Therefore the temperature at the end of the century is only affected by climate policies, not by air pollution policies (see Fig. 6a). By mid-century, when the temperature peaks in the POL cases, there is very little difference between the different air pollution policy cases. Even the counterfactual leads to only a negligible reduction of the peaking and the temperature in 2100. Therefore, even when looking at the temperature, the achievability of low stabilization targets does not depend on the stringency of air pollution policies.

Not only the absolute temperature change, but also the transient rates of warming could affect ecosystems (O'Neill and Oppenheimer, 2004). In the BASE cases, the rate of change quickly rises from around 0.2 °C per decade today to around 0.4 °C per decade in the middle of the century (see Fig. 6b). Stringent air pollution policies push the point in time when such high rates of change are reached to earlier years, but hardly affect the final level. In the POL cases, the rate of temperature change starts decreasing before 2020 and approaches zero in the middle of the century, with very little difference between different air pollution policy cases. In these cases, the stringency of air pollution policies determines behavior in the first decades and therefore the maximal rate of change. With stringent air pollution policies, the rate of temperature change could indeed be accelerated in the next decade. However, when targeting only small-scale sources, it may even be slowed down. Already from 2020 on the rate of temperature change depends more on climate policies than on air pollution policies. The acceleration of climate change due to air pollution policies seems to be a short-term effect, which is succeeded by the effects of climate policies within a decade.

The difference between the maxima of POL STRGT and POL WEAK is about 0.09 K per decade. The 90% confidence interval in 2015 is around 0.2 K per decade (see supplementary material S5). The rates of temperature change induced by different air pollution policies are within the range of uncertainty, however at the bounds. Rogelj et al. (2013) have found that climate system uncertainties have a larger influence on mitigation costs than technological uncertainties. The same seems to be the case here, where climate system uncertainties are larger than the variation due to air pollution policies.

4. Summary and discussion

In this paper we studied the interaction between different air pollution policies and the climate system. Our main findings from this study are summarized in this section.

Air pollution policies can reduce pollutant emissions substantially in the absence of climate policies. With stringent climate policies in place, emissions are already reduced, which leads to a smaller additional impact of air pollution policies.

We analyzed air pollution policies that target large-scale and small-scale sources independently. Stronger regulation of large-scale sources led to an emphasis on sulfur abatement, while stronger regulation of small-scale sources increases BC abatement. In the BASE scenario without climate policies, the stringency of air pollution policies led to considerable variation in sulfur and BC emission levels almost throughout the century. In 2030, the most stringent air pollution policies decreased SO_2 and BC emission levels by 30 and 25%, respectively. Half of the SO_2 reductions came from the power sector, whereas half of the BC reductions came from the transport sector. The weakest policies increased SO_2 emissions by 20% and BC emissions by 10%, again with the power sector and the transport sector as the most important sources, respectively. In POL scenarios variation was much smaller. Ambitious climate policies reduced SO_2

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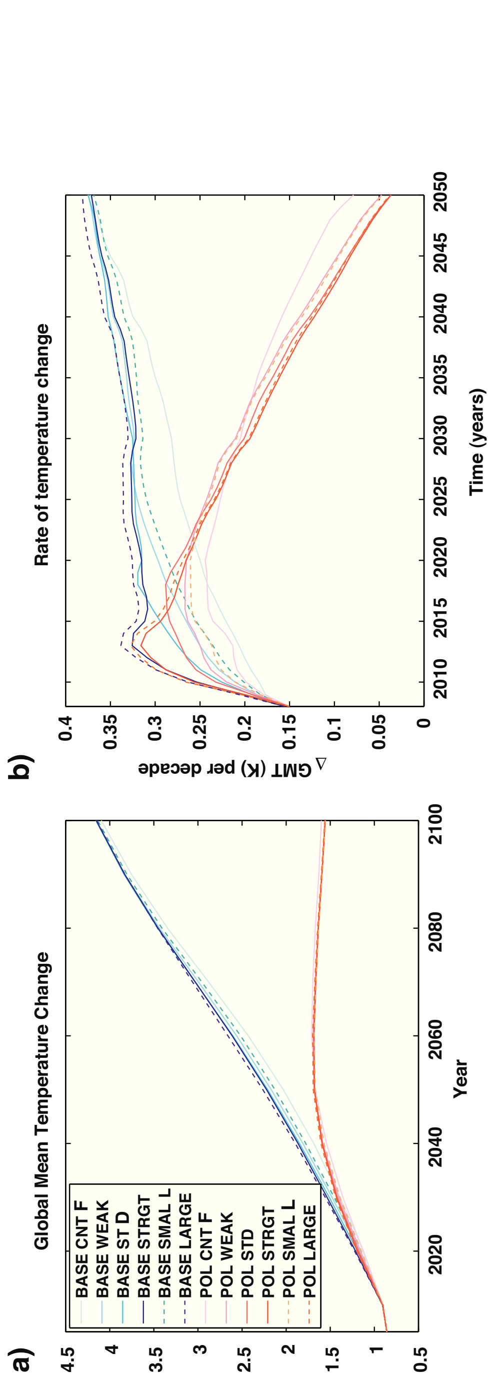

Fig. 6 – Global mean temperature increase (a) and rate of global temperature change (b) in baseline and climate policy cases under different air pollution policies. The temperature is calculated based on anthropogenic forcing, i.e. there are no variations due to solar forcing.

emissions almost as fast as and to lower levels than air pollution policies. Climate policies and air pollution policies have comparable effects on BC emissions in the first decades; afterwards the effect of climate policies dominates the effect of air pollution policies. In all cases, climate policies show a co-benefit for health as they substantially reduce air pollution.

There is considerable uncertainty in base year emission levels, especially concerning carbonaceous aerosols, as well as final emission control levels. The variation of emission pathways due to climate policies is comparable to the variation due to uncertainty in final emission control levels. Therefore the absolute levels of emissions and the exact point in time when emissions in POL STD fall below emission levels in BASE STRGT are uncertain.

Air pollution policies do not affect long-term climate targets.

Since BC is an important contributor to global warming, several previous studies have proposed that air pollution policies should focus on BC rather than sulfur. Other studies suggested that there could be a conflict of interests between air pollution policies focusing on sulfur and climate policies.

We have shown that the stringency of air pollution policies does not have a significant effect on the forcing peak or the forcing in 2100 under stringent climate policies. Air pollution policies aiming at large-scale sources, which are characterized by high sulfur content, hardly change long-term climate. Only in the absence of climate policies could air pollution policies targeting small-scale sources lower global mean temperature by some tenths of degrees Celsius. Even in a hypothetical scenario assuming no further improvements of pollution control we see only very small deviations. Temperature and radiative forcing overshoot levels are also not affected. Neither the maximal value nor the value in 2100 is affected significantly by air pollution policies. This shows that none of the studied air pollution policies endangers the feasibility of medium- and long-term climate targets. In addition to the uncertainty in emissions and emission factors there is also uncertainty in the translation to radiative forcing. Since we see only small variations in all scenarios, this geophysical uncertainty does not affect our qualitative conclusions.

Simultaneous reduction of aerosols counteracts a fraction of the reduction of Kyoto forcing, but does not neutralize it.

In scenarios with climate policies, Kyoto forcing is reduced substantially compared to baseline scenarios. The associated reduction of aerosol forcing offsets a fraction of the reduction of Kyoto forcing, but does not overcompensate. To what extent the reduction in Kyoto forcing is offset depends on the stringency of air pollution policies. More stringent air pollution policies will lead to a smaller offset in POL scenarios compared to BASE since aerosol emission are already much reduced in the BASE case. A smaller offset means that the reductions in Kyoto forcing have a higher impact, which leads to a larger difference between BASE and POL forcing. The more stringent the air pollution policies are, the larger is the difference between BASE and POL forcing. This is mainly due to differences in BASE, where the stringency of the air pollution policies has a much larger effect.

Air pollution policies may affect the rate of climate change in the short term.

Short-term temperature change can be affected by the design of air pollution policies. Independently of climate policies, air pollution policies are able to accelerate or decelerate global mean temperature change in the first decades. Without climate policies, the rate of temperature change increases throughout the first half of the century up to around 0.4 °C per decade. Weak air pollution policies decrease the rate of temperature change in the first two decades by up to 0.08 °C per decade, but have no effect on the long-term increase. Only in a counterfactual scenario without climate policies does the rate of temperature change stay below the other BASE cases until 2050 by about 0.05 °C per decade. However, this comes at the cost of very high aerosol emissions. With stringent climate mitigation policies, the rate of temperature change starts declining before 2020 and approaches zero in the middle of the century. From 2025 on, there is very little difference between the POL cases and their rate of temperature change stays below all of the BASE cases, including the CNTF. In the first decade, air pollution policies are able to influence the maximal rate of change with the scenarios varying by 0.1 °C. It is uncertain how strongly the rate of temperature change affects ecosystems, especially if higher rates of change persist for only one or two decades. Further research in this area would be valuable to assess the short-term impacts of air pollution policies.

A caveat of our study is the regional distribution of emissions. Since aerosols have a lifetime of the order of days in the atmosphere, they also impact the local climate. This effect cannot be captured in our approach, where we use the reduced complexity climate model MAGICC6, which consists of four regions (northern and southern hemisphere, land and ocean). Regional effects on a smaller scale cannot be captured with this model and would be subject to further research.

There is no tradeoff between clean air and climate policies.

Our findings have important implications for climate policies. They show that the stringency of air pollution policies does not significantly affect the magnitude of the climate mitigation challenge. Thus, there is no conflict of objectives between clean air and climate policies, as suggested by previous studies. To the contrary, our results confirm that climate policies induce substantial co-benefits to air pollution policies, by driving down fossil fuel use. Stringent air pollution policies decrease air pollution, both from carbonaceous aerosols and from sulfur, regardless of climate policy, thus leading to a positive effect on human health and ecosystems. At the same time, even stringent air pollution policies have almost no influence on medium- and long-term climate targets. These results suggest that air pollution policies can be implemented without negative interference with climate policies. We thus conclude that the focus of climate mitigation efforts should remain on the reduction of long-lived greenhouse gases.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2014.04.009.

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Supplementary Material

S1 Emission modeling

In 2005, total global anthropogenic sulfur emissions amounted to 58.1 TgS, with 67% coming from fossil fuel combustion in the energy system and industry, 17% from residential and transportation sectors, 13% from industrial processes, and 3% from land-use and land-use change (EDGAR 2011). Coal and crude oil usually contain 1-2% sulfur by weight. About half of the global sulfur emissions arise from coal combustion and another 25% from oil combustion (Smith et al. 2001). Sulfur emissions from natural gas can be neglected in our model because it has to be desulphurized for transport in order not to damage the pipelines. This leads to very low emission factors which account for less than 1% of the total emissions. Traditional biomass contributes around 1% of global sulfur emissions (Smith et al. 2001) and is also neglected. The most important sources of BC emissions open burning (about 42%) and contained combustion of coal, biofuel, and transportation fuels (Bond et al. 2004). BC and OC result from an incomplete combustion process of fossil fuels and biomass. Specific emission factors depend on the type of fuel and the details of the combustion process as air mixture and temperature. Since combustion processes vary within sources, this is a source of uncertainty of emission factors. Sulfur emissions in REMIND are calculated using time-dependent, region- and technology-specific emission factors for all technologies using coal and oil. BC and OC emissions are calculated the same way, including emissions from biofuels. There is considerable uncertainty regarding not only aerosol emission but also aerosol forcing. Some studies have even identified BC as the second largest contributor to global warming after CO_2 (Jacobson 2010; Ramanathan & Carmichael 2008). A recent assessment by Bond et al. (2013) suggests that BC direct forcing may be underestimated by a factor of three. However, the net current effect of all black-carbon rich emission sources over the industrial era, including the co-emittants and indirect effects, is estimated to be close to zero (Bond et al. 2013). The influence of climate uncertainty on the results of this study is assessed in the supplementary material S5.

Smith (Smith et al. 2005) formulates a connection between affluence, measured in GDP per capita, and the decline of sulfur emission factors. The maximal or uncontrolled emission factors EF_{max} [Tg S / TWa] are determined by the sulfur content of the fuel and the ash retention. A certain fraction of these emissions can be controlled with end-of-pipe technologies. The maximum level of control f_{max} depends on the technology and the fuel. The percentage of controlled emissions increases with increasing GDP per capita. This function is s-shaped and defined by the mid-point $GDPCAP_0$ (units of US$2005 per capita), where half of the possible reductions are realized, and the range τ (also in units of US$2005 per capita) in which 90% of the reductions occur. The functional form of the fraction of controlled emissions $f_{control}$ is

$$f_{control}(t) = \frac{f\_max}{1+\exp\left(-\frac{c}{\tau}\left(GDPCAP(t)-GDPCAP_{0(t)}\right)\right)}, \quad (1)$$

where c is a scaling constant equal to 2 * ln(9) = 4.394.

The above formulation of the controlled emissions fraction yields the emissions factor

$EF(t) = EF_{max} * (1 - f_{control}(t))$.

We use this approach to calculate time-dependent, region- and technology-specific emission factors for sulfur, BC and OC. EF_{max} and f_{max} are the same in all scenarios. EF_{max} depends on the fuel type and, in case of BC and OC, on the combustion process. For each aerosol and fuel type it is specified for power plants, residential and commercial buildings, industry and transport (see supplementary material S2 for parameter values). Since the sulfur content of coal varies between regions, it is also region specific. The maximum level of control f_{max} is assumed to be only fuel and technology dependent. It is kept constant over region and time. Values are taken from Smith et al. (2005) for SO_2 and based on Bond (2004) for BC and OC. For the standard case, we take values for τ from Smith et al. (see supplementary material S2). $GDPCAP_0$ decreases at 0.075% per year in Smith's approach to account for technological diffusion. To reduce numerical complexity, we keep $GDPCAP_0$ constant and choose the value such that it is equal to the value in Smith's approach at the point in time it is reached. These two parameters are varied according to different scenario assumptions (see Section 2.3 and supplementary material S2). For the stringent scenarios, we assume that air pollution policies are already implemented at an earlier stage of development, thus the per-capita threshold level $GDPCAP_0$ is assumed to be smaller. Conversely, weak policies imply later reduction of emission factors and therefore a higher $GDPCAP_0$. We vary this parameter by a factor of 2 in both directions. To ensure consistency with base year emission factors, we have to adapt τ accordingly.

S2 Parameters for aerosol emission factors

Model region	*Countries*
AFR	Sub-Saharan Africa w/o South Africa
CHN	China
EUR	EU27 countries
IND	India
JPN	Japan
LAM	All American countries but Canada and the US
MEA	North Africa, Middle Eastern and Arab Gulf Countries, Resource exporting countries of FSU, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states, Turkey, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

Table S1: World regions in REMIND.

Region	*$GDPCAP_0$ [k\$ / cap]*			*τ [k\$ / cap]*		
	Std	*Weak*	*Strgt*	*Std*	*Weak*	*Strgt*
AFR	10	18	5.5	12	23	5.8
CHN	11	21	6	12	30.2	2.9
EUR	25	25	25	12	12	12
IND	12	22	6.7	12	24.3	5.5
JPN	12	12	12	5	5	5
LAM	20	34	11	20	44.8	4.1
MEA	17	29.5	10	12	27.4	3.4
OAS	12	22	7	12	28.1	4
ROW	15	15	15	12	12	12
RUS	14.5	14.5	14.5	12	12	12
USA	32	32	32	25	25	25

Table S2: Key parameters for evolution of emission factors for different air pollution policy assumptions.

Region	*Coal, energy*	*Coal, industry*	*Coal, residential*	*Oil, energy*	*Oil, industry*	*Oil, residential*	*Oil, transport*
AFR	14.3	14.3	13.5	8	5	5	4
CHN	9.5	9.5	9	8	5	5	3.5
EUR	16.3	18.1	18	8	5	5	5
IND	9.4	9.4	9	7	5	5	6
JPN	15.2	15.2	14.4	15	5	7	6
LAM	16.9	17.1	16.2	18	7	7	3
MEA	15	14.5	14.4	20	10	5	3.5
OAS	8.3	8.5	8.1	7	5	5	3
ROW	17.3	18.1	18	12	7	7	3.5
RUS	10.5	10.9	10.8	15	7	7	4.5
USA	18.7	19	18	15	5	5	6
f_{max}	0.9	0.45	0.75	0.75	0.75	0.75	0.9

Table S3: Uncontrolled aggregate sulfur emission factors in [Tg S / TWa] for all regions and sectors and maximum level of emission control for all sectors (constant for all regions).

Sector	*Uncontrolled BC emission factor*	f_{max}	*Uncontrolled OC emission factor*	f_{max}
Coal, energy	0.012	0.99	0.1	0.99
Coal, industry	0.7	0.5	0.4	0.5
Coal, residential	4	0.5	10	0.5
Oil, energy	0.07	0.99	0.01	0.99
Oil, industry	0.5	0.99	0.01	0.99
Oil, residential	2	0.3	1	0.3
Oil, transport	0.9	0.96	1	0.96
Biomass, energy	0.09	0.99	0.4	0.99
Biomass, industry	0.7	0.5	2	0.5
Biomass, residential	4	0.65	30	0.65

Table S4: Uncontrolled aggregate BC and OC emission factors in [Tg BC / TWa] and [Tg OC / TWa], respectively, and maximum level of emission control for all sectors (constant for all regions).

S3 Air pollutant control costs

REMIND sector	Main pollutant	Control technology	Average annual cost effectiveness [$/ton]
Energy, Coal	SO_2	Wet Flue Gas Desulfurization	1,536
Energy, Oil	SO_2	Wet Flue Gas Desulfurization	4,524
Energy, Biomass	BC	Fabric Filter (Pulse Jet Type)	117
Industry, Coal	SO_2	Wet Flue Gas Desulfurization	1,536
Industry, Oil	SO_2	Wet Flue Gas Desulfurization	4,524
Industry, Biomass	BC	Fabric Filter (Pulse Jet Type)	117
Residential, Coal	BC	Fabric Filter (Pulse Jet Type)	117
Residential, Oil	BC	Dry ESP-Wire Plate Type	110
Residential, Biomass	BC	NSPS compliant Wood Stoves	2,000
Transportation, Oil	BC	Voluntary Diesel Retrofit Program: Diesel Particulate Filter	30,000

Table S5: Air pollutant control technologies and costs.

S4 Sensitivity of results to choice of fmax

In our approach, we use four independent parameters per region and sector (see Eq. 1). Two of them are varied to emulate different air pollution policies. A third parameter, the level of uncontrolled emissions, is determined by historical emissions. In case of sulfur, an upper bound can be estimated by the average sulfur content in coal and oil. However, there is some uncertainty in historical emissions. For sulfur, uncertainty in global emissions is estimated to be roughly 10% (Smith et al. 2011). Bond et al. (2013) estimate 90% emission uncertainty bounds for energy-related emissions in 2000 to be 1.2-15 Tg.

The last parameter determines the maximal level of emission control. To analyze the dependency of aerosol emissions on our modeling assumptions, we perform a sensitivity study of the maximal fraction of emission control. In addition to the standard case, we run four more scenarios with the parameter values given in Table S5. For most sectors we vary f_{max} in the range of 20-30%. One exception is coal in the power sector. Here flue-gas desulphurization is able to reach desulphurization rates of more than 90%. High levels of emission control have already been implemented in many countries. Therefore we did not assume much lower values.

	f_{max}	*Coal, energy*	*Coal, industry*	*Coal, residential*	*Oil, energy*	*Oil, industry*	*Oil, residential*	*Oil, transport*
SO_2	Standard	0.9	0.45	0.75	0.75	0.75	0.75	0.9
	High	0.95	0.65	0.85	0.85	0.85	0.85	0.95
	Very high	0.99	0.85	0.95	0.95	0.95	0.95	0.99
	Low	0.9	0.35	0.60	0.60	0.60	0.60	0.7
	Very low	0.9	0.25	0.45	0.45	0.45	0.45	0.5
BC	Standard	0.99	0.5	0.5	0.99	0.99	0.3	0.96
	High	0.99	0.6	0.6	0.99	0.99	0.45	0.99
	Very high	0.99	0.7	0.7	0.99	0.99	0.6	0.99
	Low	0.95	0.4	0.4	0.9	0.9	0.2	0.9
	Very low	0.90	0.3	0.3	0.7	0.7	0.1	0.7
OC	Standard	0.99	0.5	0.5	0.99	0.99	0.3	0.96
	High	0.99	0.6	0.6	0.99	0.99	0.45	0.99
	Very high	0.99	0.7	0.7	0.99	0.99	0.6	0.99
	Low	0.95	0.4	0.4	0.9	0.9	0.2	0.9
	Very low	0.90	0.3	0.3	0.7	0.7	0.1	0.7

	f_{max}	*Biomass, energy*	*Biomass, industry*	*Biomass, residential*
BC	Standard	0.99	0.5	0.65
	High	0.99	0.6	0.8
	Very high	0.99	0.7	0.95
	Low	0.9	0.4	0.5
	Very low	0.7	0.3	0.35
OC	Standard	0.99	0.5	0.65
	High	0.99	0.6	0.8
	Very high	0.99	0.7	0.95
	Low	0.9	0.4	0.5
	Very low	0.7	0.3	0.35

Table S6: Variation of maximal level of emission control fmax.

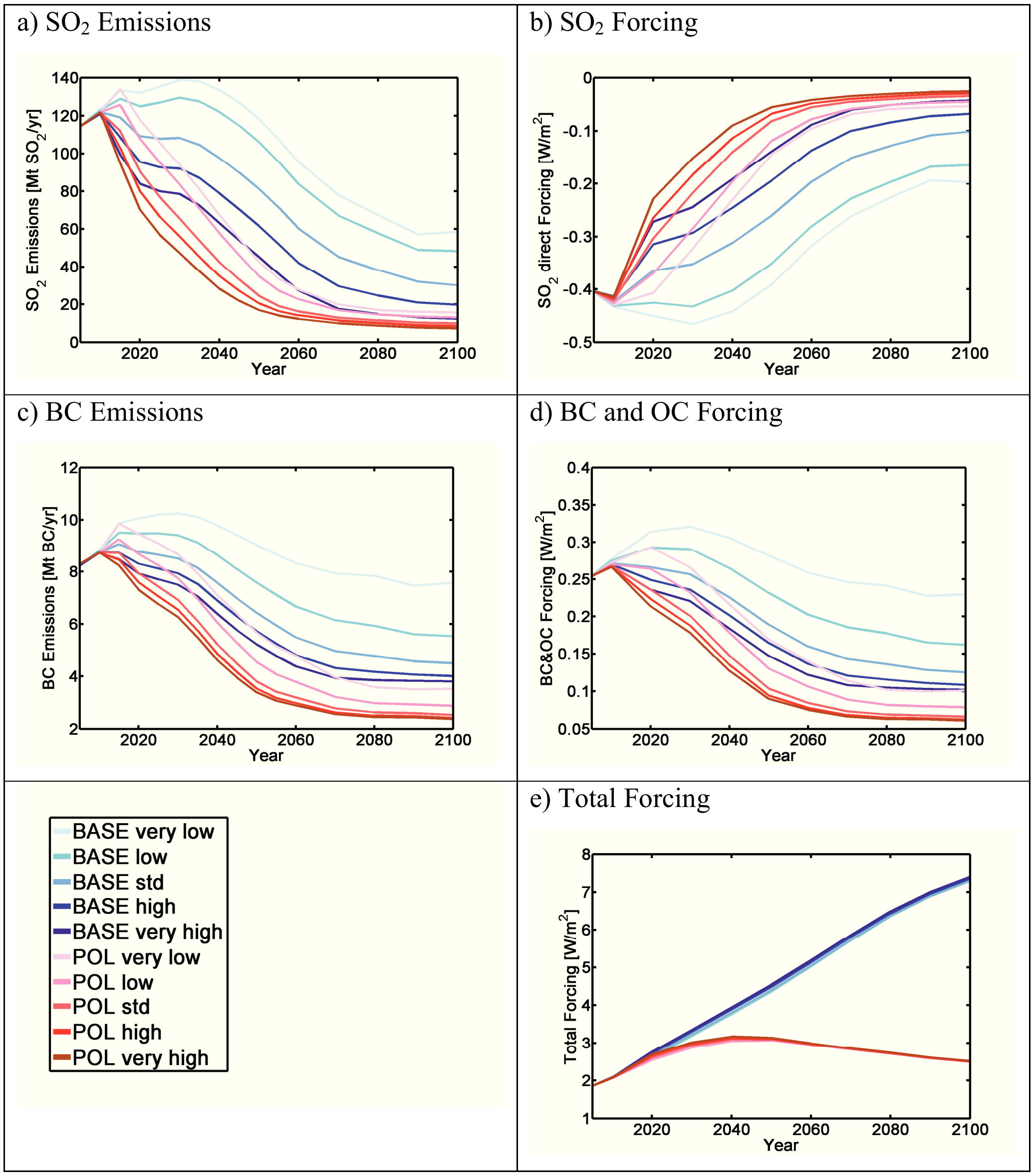


Figure S1: Aerosol emissions and forcing with different maximal levels of emission control.

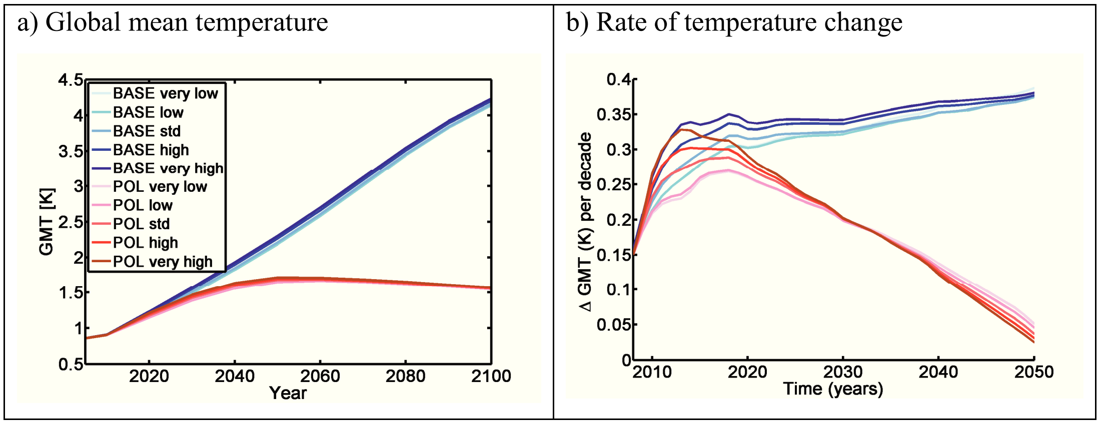
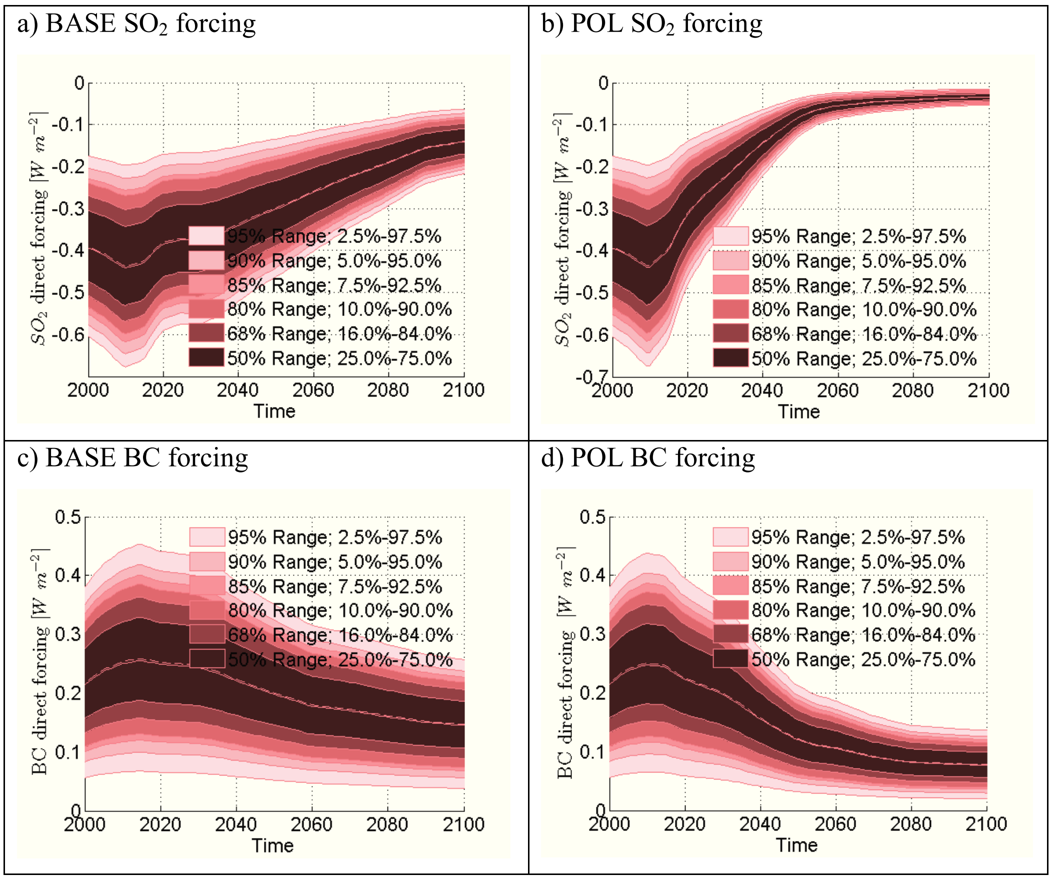


Figure S2: Temperature and rate of temperature change for different maximal levels of emission control.

S5 Uncertainty in the climate system

Figure S3 shows 90% confidence intervals of several climate indicators using MAGICC 6. A recent study (Bond et al. 2013) indicates, that direct BC forcing may have been underestimated previously. This is not included here, but suggests that uncertainty with respect to BC forcing may be larger.



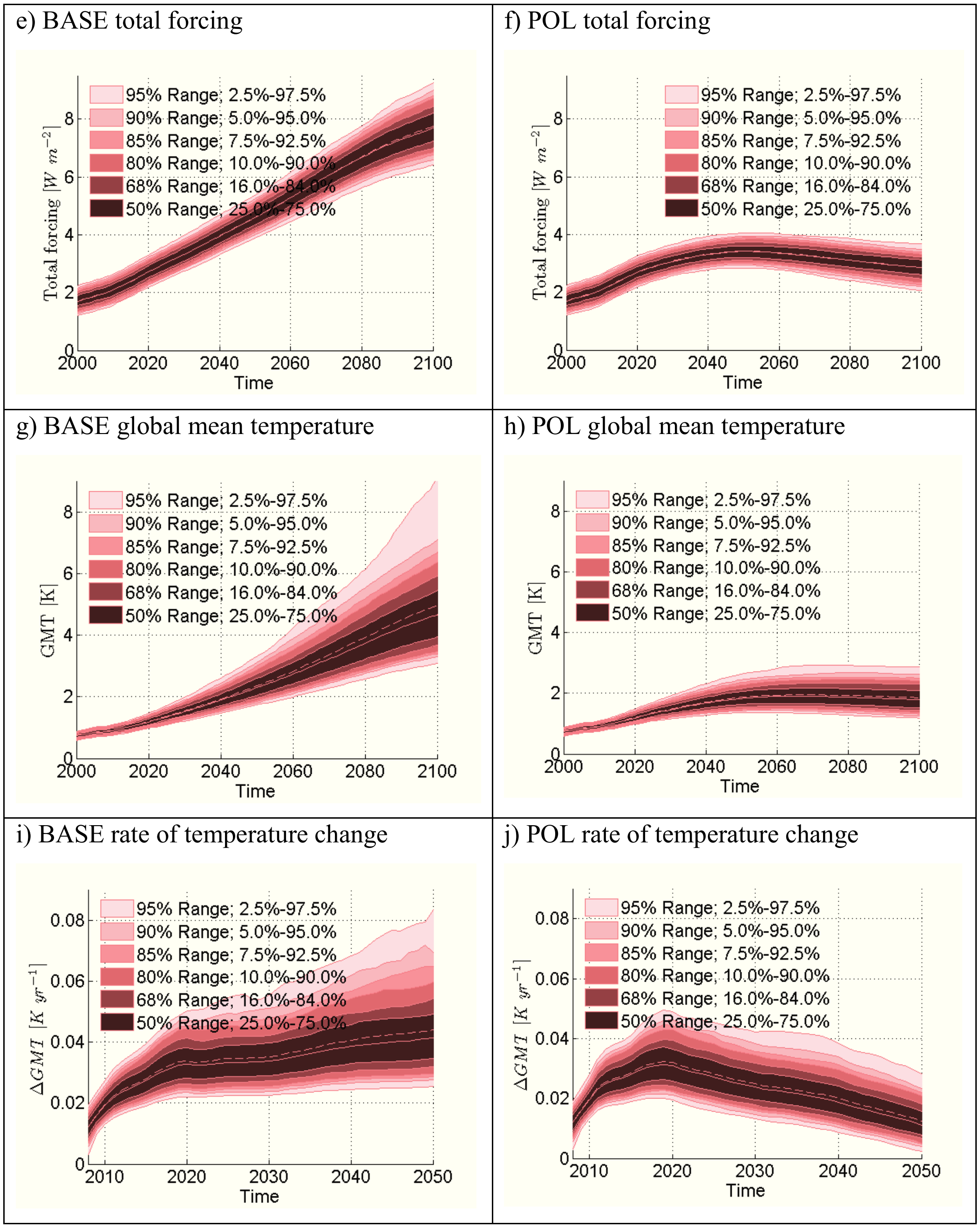
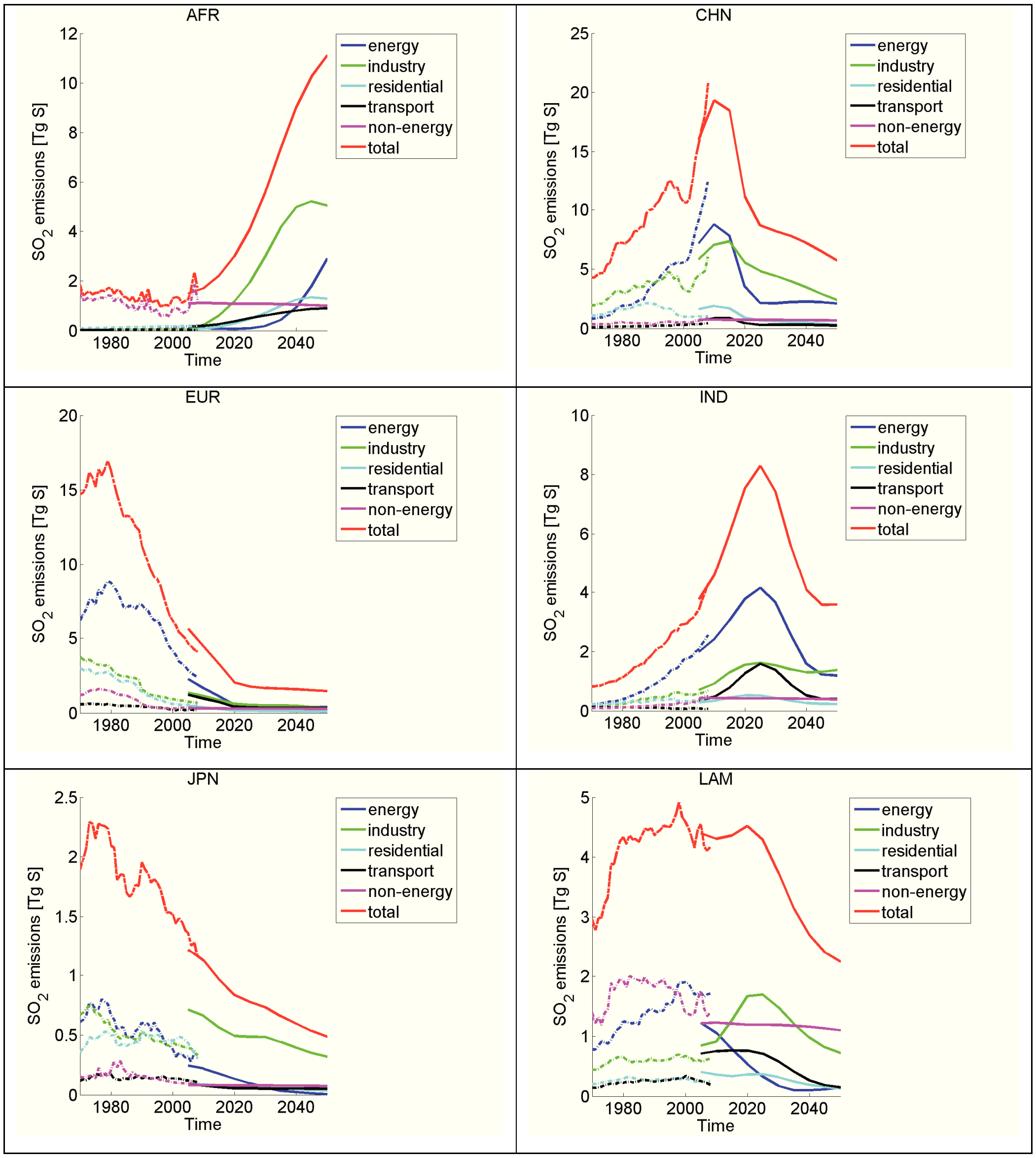


Figure S3: 90% uncertainty range for BC, SO2 forcing, and total forcing, temperature and rate of temperature change for BASE STD (left) and POL STD (right).

S6 Regional and sectoral aerosol emissions



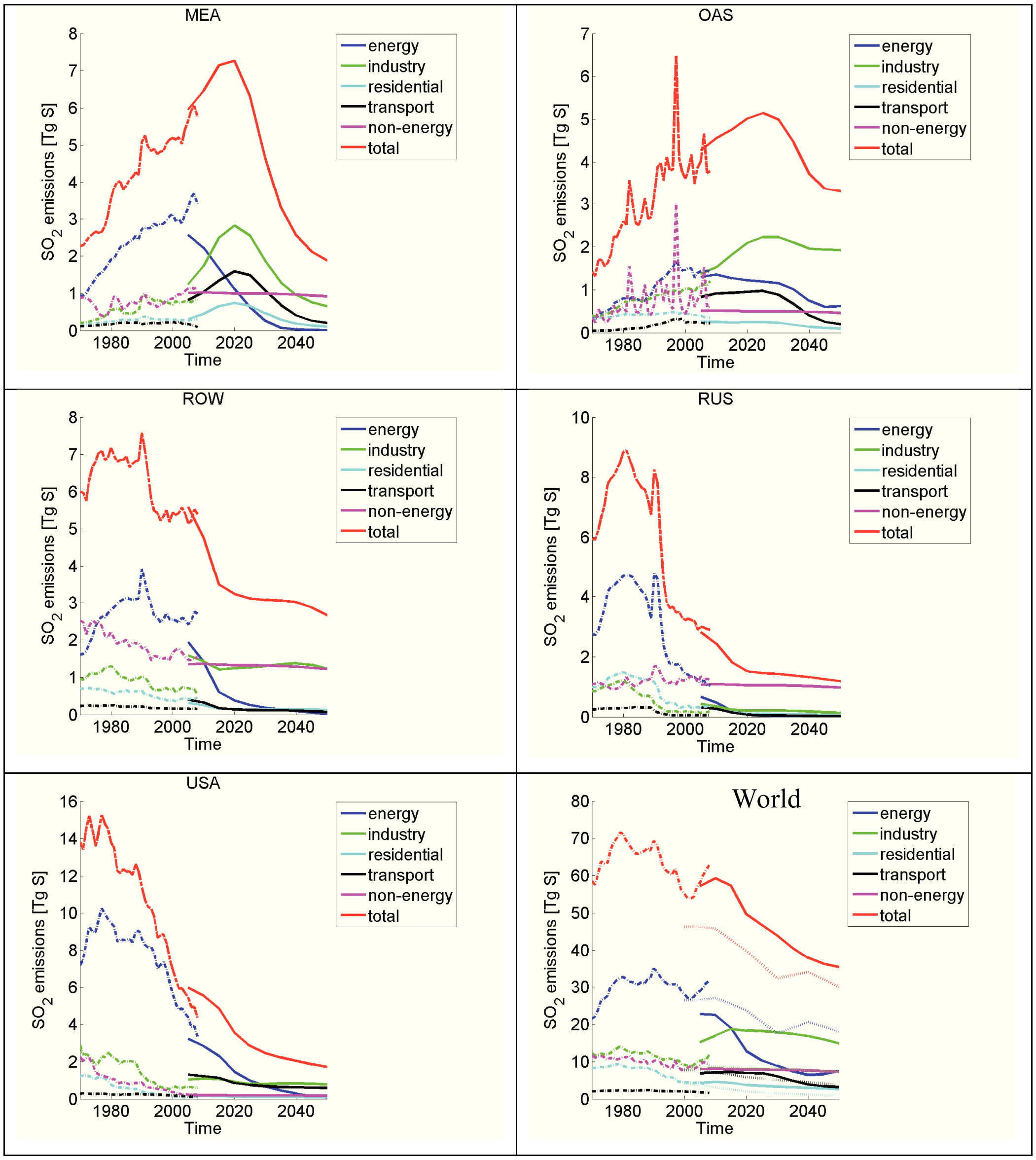
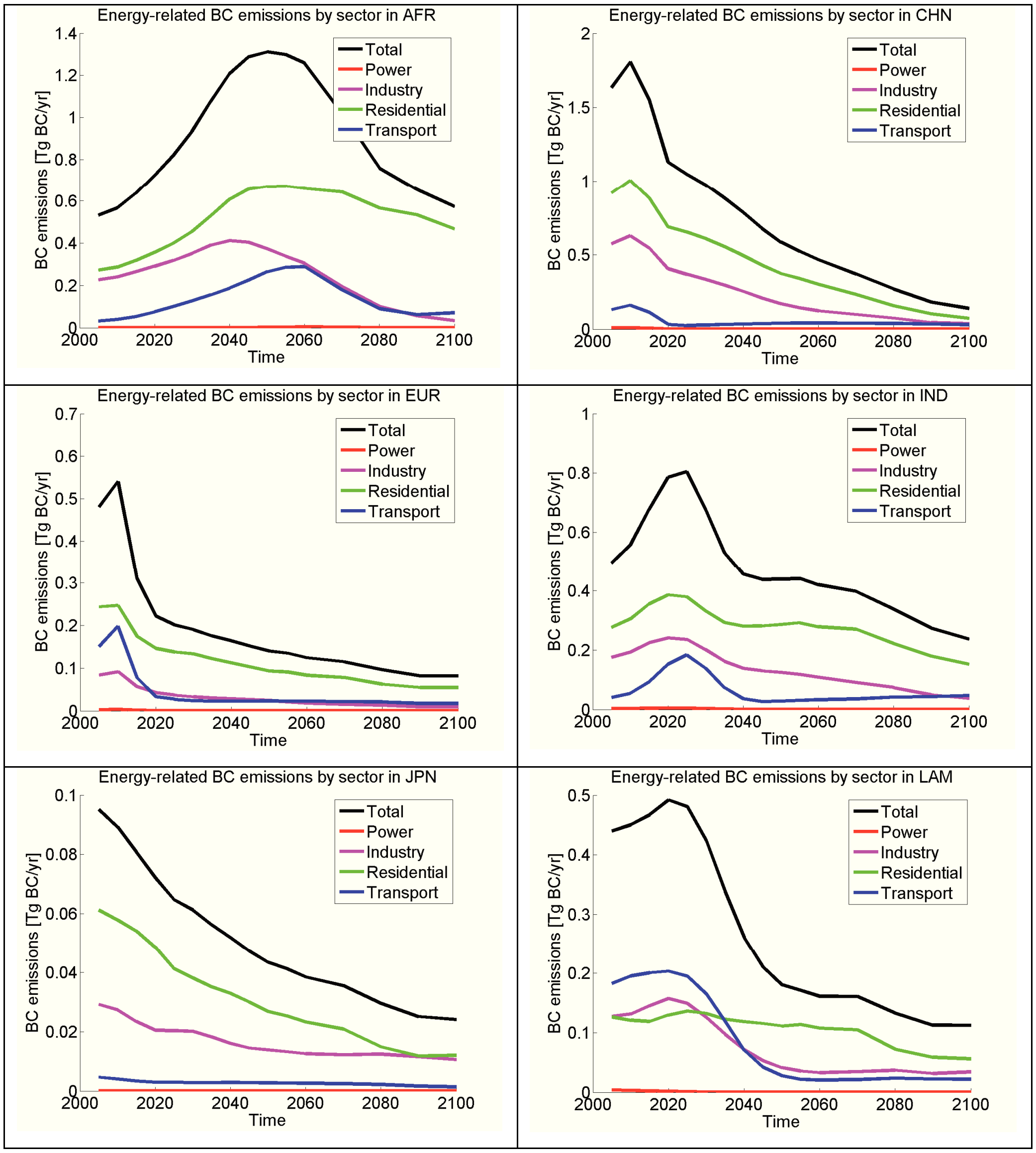


Figure S4: Regional and sectoral SO2 emissions in [Tg S] for BASE STD. Solid lines are REMIND emissions, dashed lines are from EDGAR v4.2. The global plot shows RCP6.0 (Fujino et al. 2006; Hijioka et al. 2008) results in dotted lines for comparison.


Energy-related BC emissions by sector in AFR
Energy-related BC emissions by sector in CHN
Energy-related BC emissions by sector in EUR
Energy-related BC emissions by sector in IND
Energy-related BC emissions by sector in JPN
Energy-related BC emissions by sector in LAM
BC emissions [Tg BC/yr]
Time
Total
Power
Industry
Residential
Transport

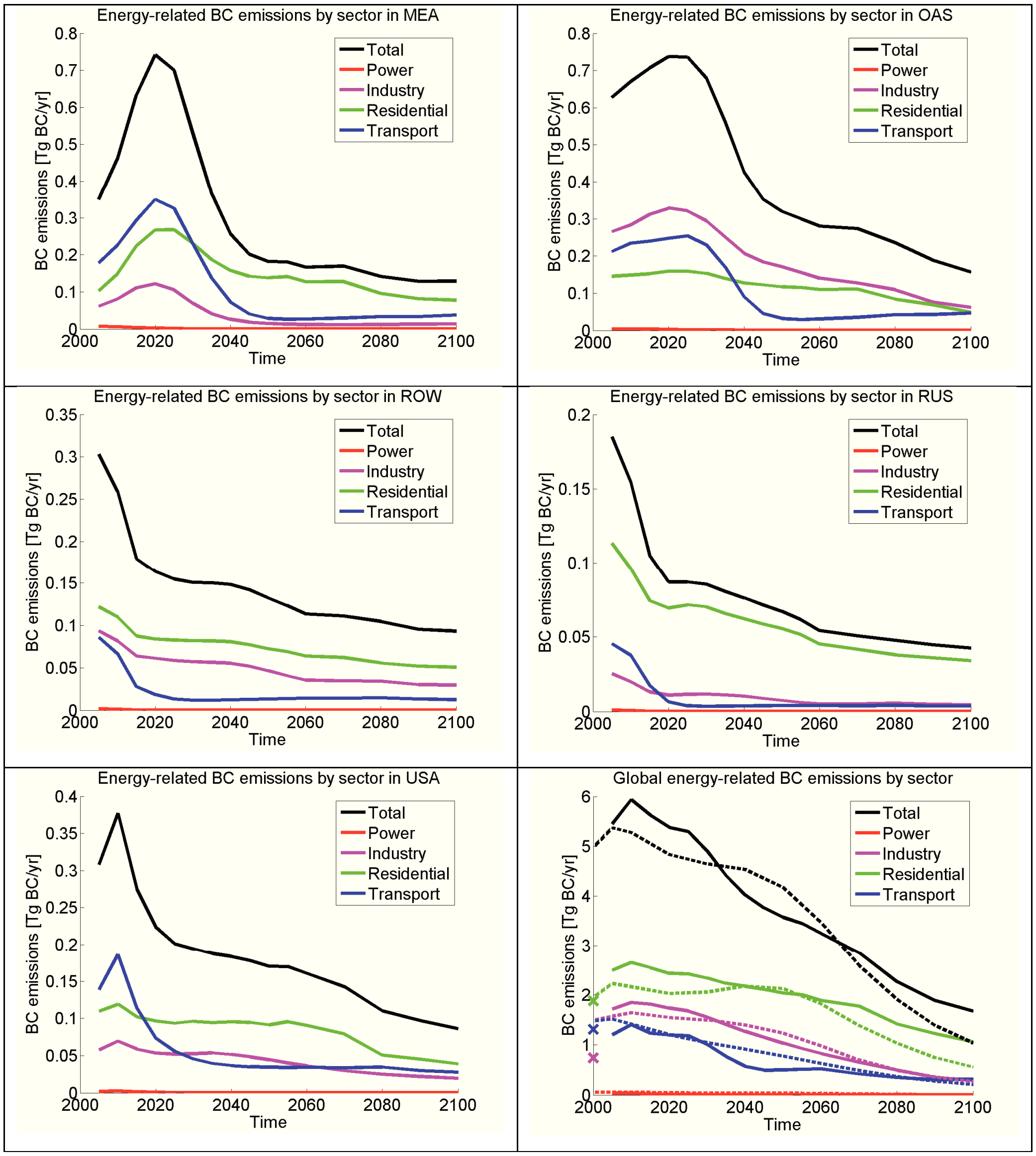


Figure S5: Regional and sectoral BC emissions in [Tg BC] for BASE STD. Solid lines are REMIND emissions. The global plot shows RCP6.0 (Fujino et al. 2006; Hijioka et al. 2008) results in dotted lines and 2000 values from Bond et al. (2013) for comparison.

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Chapter 7

Synthesis and Outlook

The main objective of this thesis has been to analyze how reductions in non-CO_2 long-lived GHGs and aerosols complement CO_2 emission reductions in the achievement of low stabilization scenarios. We analyzed the energy demand of developing countries as it is currently represented in integrated assessment models. This is an important factor not only for correct estimates of emissions and available emission budgets, but also for international climate policy, as it is one reason for governments not to join treaties. Another important factor is the inclusion of non-CO_2 Kyoto gases in emission budgets. In recent years there has been broad scientific agreement that they have to be included, yet there has been an ongoing debate as to the appropriate method. In our study, we analyzed global and regional economic impacts of alternative greenhouse gas emission metrics. As a third factor we investigated the interdependence of bioenergy supply and the availability of CCS. Besides Kyoto gases, aerosols contribute a major fraction to today's radiative forcing. In a last study we quantified impacts of different aerosol emission scenarios on short- and long-term climate. These emission scenarios can be interpreted as more or less stringent air pollution policies targeting different sectors of the energy system. We analyzed whether there are conflicts of objective between air pollution and climate policies.

I will first present a synthesis of the major findings of this thesis along the research questions formulated in Chapter 1. In the second part, I will discuss the results and relate them to other approaches. Finally, I will address further research possibilities.

7.1 Synthesis of results

Do current integrated assessment models underestimate the energy demand in developing countries?

Globally, humankind is faced with the twin challenges of mitigating climate change and overcoming poverty. Despite the urgency of solving the climate problem, mitigation policy should not trap developing countries in a state of poverty. At the same time, future development processes should avoid technological lock-ins, e.g. in carbon-intensive infrastructures or energy systems.

When looking at low-stabilization scenarios produced by IAMs, we find that historical correlations between economic growth and energy use are discontinued in mitigation scenarios, both with respect to a postulated (and observed) energy threshold as well as with respect to increasing energy use in the course of development. In model results for mitigation scenarios, final energy demand in developing regions stays approximately at current (low) levels, whereas per capita GDP rises significantly. At the same time, developing countries are projected to face higher energy intensity improvements than developed countries. At first sight, the model results seem to be either not realistic or driven by very strong implicit assumptions.

To understand the plausibility of model results, the most important question is whether developing countries will be able to decouple their growth from energy use and - looking at the differences between baseline scenarios without climate policies and climate policy scenarios - how fast this can be achieved. We are rather pessimistic about it being possible for low income countries to develop without increasing their level of energy use, given the indicated need for energy to drive GDP growth. In addition to energy required to satisfy basic needs at the household level, energy is also embedded in the construction of infrastructure when affluence levels go beyond the satisfaction of basic needs. All countries that have reached higher development levels in the past have increasingly used energy-intensive inputs like steel and cement and it is hardly plausible that this correlation will break, at least in the near future. This impression is confirmed by an analysis of the current developing process in India or China (Steckel et al., 2011). Recent results from the literature (Jakob et al., 2012) also imply that historical patterns of energy use are repeated for developing countries and leapfrogging in this respect will be hard to achieve if capital accumulation will remains an important driver of economic growth in the future. However, assuming that scenario results are robust, we can provide a twofold interpretation:

First, only with massive improvements of energy intensity will it be possible to dramatically reduce the energy used for capital accumulation as compared to patterns observed in the past. This result highlights the urgent need for drastic efficiency improvements and the simultaneous provision of the latest technologies to developing countries. Our results imply that bringing production processes of infrastructure inputs towards their thermodynamic limits might allow scenario results for developing countries to be achievable in reality. However, considering historic trends, no dramatic improvements in the efficiency of these processes can be expected in the near-term. Thus the efficiency gains implicitly assumed by the models seem to be out of reach. Alternatively, a total or partial replacement of energy-intensive inputs by low energy alternatives is theoretically conceivable, e.g. by newly developed materials or methods; however, this option requires a significant leap of faith.

The second interpretation is that developing countries might reach high levels of economic development without accumulating energy-intensive capital. Of course, for our analysis focusing on infrastructure, it is also conceivable that necessary inputs are imported; however, as both steel and cement are not easy to transport, importing these inputs over large, trans-regional distances seems to be rather unlikely and would be unprecedented in the past. Also, it is not indicative from scenario results that energy for steel and cement is provided in other regions. In principle it is possible to imagine societies whose economic growth is not based on capital accumulation, thinking of a service-oriented society.

Both interpretations imply strong underlying assumptions. Some of the results are based on the ReMIND-R model, which neither explicitly represents the energy needs for the infrastructure build-up during the development process nor includes any explicit energy access targets for development. We have shown that the general tendency of very low levels of final energy per capita consumption is robust over a whole set of different models. Our results point to the need to spell out the details of energy demand structures more explicitly, in particular for the developing world. Analyzing energy needs at different stages of development is a promising future area of research that is in its infancy in the IAM community (Krey et al., 2012; Daioglou et al., 2012). A possible outcome of calibrating IAMs to such bottom-up derivations of energy demand could be that current mitigation scenarios are too optimistic with respect to energy consumption in developing countries. Such a finding could challenge one of the most important conclusions derived by IAMs, namely that mitigation costs can be expected to be comparatively modest. In general, this analysis raises the question whether a stronger differentiation between developed and developing countries is necessary in IAMs. For example, IA modelers could represent energy access policy targets in terms of a minimal energy input level that should be achieved to guarantee reasonable development levels. As of today, these questions - along with other important issues of sustainability - are not taken into account in most IAM analyses.

How does the choice of greenhouse gas emissions metric affect transformation pathways?

Several previous studies showed that global economic costs decrease significantly when non-CO_2 Kyoto gases are limited as well (Weyant et al., 2006; van Vuuren et al., 2006). This can be done by either defining separate budgets or pathways for all specific gases, or by converting these emissions to CO_2 equivalents and including them in one single budget. For the latter approach a conversion metric has to be defined. The most widely used metric so far is the 100-year global warming potential (GWP), which has been adopted e.g. in the Kyoto protocol. It is a simple and fixed metric; however, it has its shortcomings. Physicists and economists criticized the GWP on economical and physical grounds (Schmalensee, 1993; O'Neill, 2000; Manne and Richels, 2001; Shine et al., 2005), and a number of alternative metrics have been proposed. In our study we investigated the influence of the choice of metric on global and regional economic costs and on medium term climate indicators. For this purpose we ran several scenarios employing a variety of metrics, time-dependent as well as time-fixed, under a climate policy of not exceeding 2 °C in 2100.

We found that the choice of metric determines medium term emission levels of CH_4.

Metrics with low exchange ratios allow for higher CH_4 emissions in the beginning. Towards the end of the century, CH_4 abatement options are fully exhausted in all scenarios, which leads to equal CH_4 emissions and radiative forcing in 2100. This leads to similar radiative forcings for other substances, too. Therefore CO_2 emission pathways show only moderate variations. However, one has to keep in mind that the choice of metric does affect the nominal budget substantially. A high exchange ratio for CH_4 may lead to earlier emission reductions, but nevertheless increase the CH_4 budget in terms of CO_2 equivalents. When deciding on a multi-gas emission budget, it is crucial that the metric is defined first and the global budget is chosen accordingly. Since global costs are dominated by CO_2 mitigation, we find that they are only weakly affected by alternative metrics. We find that there is a trade-off between global costs and transient climate change. Metrics with relatively high near-term CH_4 exchange ratios like GWP20 and to a lesser extent also GWP100 reduce CH_4 emissions early in time, which leads to a lower maximum temperature and a lower rate of temperature change. In return they have higher global costs. However, they have potential health benefits due to a lower CH_4 burden, which leads to less tropospheric ozone. The monetary value of these benefits was neglected in our cost estimate.

One major gap in previous literature was the evaluation of regional and sectoral costs. In our study, we analyzed regional mitigation costs under a resource sharing allocation scheme with per-capita convergence. Under this scheme, permits are allocated according to historical emissions in 2010, and equal per capita emissions starting in 2050. Between 2010 and 2050, regional shares in global emissions are interpolated linearly. Though there is a small effect on global costs, we find that alternative metrics may lead to regional redistributions due to trade effects of fossil fuels and shifts in emissions permit trade. Changes in CO_2 emission trajectories are correlated with changes in CO_2 prices, which can affect the energy system and lead to changes in regional distributions. A higher CO_2 price leads to less oil and gas consumption and therefore to lower oil and gas resource prices. Fossil fuel exporters have lower profits, while fossil fuel importers have lower fossil fuel import costs. However, due to the higher CO_2 price, the cost for final energy from fossil fuel use is still higher. In addition to these shifts, distributional issues may be enhanced if one considers permit trade. In this study we considered a per capita convergence of emission allowances so that in 2050 the per capita endowment with emission permits is equal across all regions. A high CH_4 exchange rate leads to a higher nominal budget. This is favorable for regions with an emphasis on CO_2, as their emission budget increases, but their nominal emissions increase only a little. Regions with an emphasis on CH_4, on the other hand, face a large increase in nominal emissions, which outweighs the increase of their emission budget. Therefore they have to buy more permits. This is mainly the case for developing and emerging economies. Our results imply that the interplay of permit allocation and choice of metric can have a considerable influence on regional costs and benefits. National or regional emission caps should therefore be contingent on the chosen metric. The same argument holds for sectoral distributions. There is little difference in actual emissions across the different scenarios, leading to comparable mitigation costs. CH_4 intensive sectors like agriculture suffer from high CH_4 exchange ratios if permit trade is considered due to rising nominal emissions.

Our results suggest that in terms of global costs the currently used GWP100 offers a good compromise between economic efficiency and transient climate targets. It might also offer health benefits due to reduced methane concentration, which leads to reduced tropospheric ozone concentration. It is important to keep in mind that greenhouse gas emission metrics do not only differ in terms of the emission pathways and economic costs induced, but also in terms of their institutional requirements. In contrast to the relatively simple physical metrics, economic metrics complex modeling tools, and depend strongly on structural and normative assumptions. Given that the currently used GWP100 performs reasonably well despite its conceptual simplicity, climate negotiators should consider carefully whether it is worth renegotiating greenhouse gas emission metrics, instead of focusing efforts on reaching an urgently needed deal in comprehensive long-term emission reductions.

How do bioenergy deployment and revenues depend on the availability of CCS, stringency of climate target, and bioenergy supply?

Bioenergy is an interesting mitigation option for two reasons: its versatility and the possibility to create negative emissions if it is combined with CCS. Bioenergy can be used to produce various energy carriers such as liquid fuels, heat, electricity, or solids. Due to its low CO_2 emissions, it can be used to decarbonize any sector. This makes bioenergy particularly valuable. In our study, we analyzed the deployment of bioenergy in scenarios with full technology availability, with bioenergy supply limitied to 100 EJ/yr, and without CCS. These three technology scenarios were combined with climate mitigation targets of 3.7 Wm^{-2} radiative forcing not to exceed and 2.8 Wm^{-2} in 2100 with overshooting before. We investigated the value of bioenergy for climate change mitigation, the structure of energy and carbon revenues across different bioenergy technologies, and its interaction with the deployment of fossil fuels.

Our study shows that bioenergy is predominantly used to produce liquid fuels in almost all scenarios. There are few low-carbon alternatives to fossil fuels, which makes bioenergy an important mitigation option in the transport sector. If CCS is available, it is also used in the production of hydrogen or other technologies with high capture rates. The value of bioenergy is determined by both its energy value and the value of negative emissions. This leads to a correlation of bioenergy price and carbon price. With rising carbon price the catpure rate becomes the crucial deciding factor in terms of which conversion routes are taken. High carbon prices induce investments in technologies that would not be built for the purpose of energy production only. For these technologies, the carbon value tends to exceed the energy value, leading to more revenues from emission permits than from energy production.

BECCS can be a crucial mitigation option with high deployment levels and a high technology value, particularly for low stabilization targets. The value of bioenergy and BECCS increase with the stringency of the mitigation target. In the 2.8 Wm^{-2} scenario of our study, global mitigation costs almost double if bioenergy supply is limited, and more than triple if CCS is not available.

Due to the creation of negative emissions, more biomass use allows for higher deployment of fossil energy. Thus bioenergy can be a substitute or a complement for fossil fuels, depending on the climate target. However, one has to keep in mind that a prolonged deployment of fossil fuels with the expectation of long-term negative emissions could be a risky strategy, since both biomass potential and the availability of CCS are uncertain. If emission reduction were postponed, the already high demand and willingness-to-pay for biomass under a stringent climate target would increase further. In our model, biomass prices exceed average production costs, giving rise to considerable land rents for producers. The resulting large-scale bioenergy production could induce high pressure on the agricultural sector with possible unintended negative impacts on land-use systems, such as competition with food production, reduction of biodiversity, and additional greenhouse gas emissions.

Can air pollution policies accelerate global warming?

Recent publications suggested that a fast reduction of aerosol emissions, especially SO_2, could accelerate global warming and make ambitious climate protection targets harder to reach or even unachievable (Ramanathan and Feng, 2008; Kopp and Mauzerall, 2010). Other studies called for reductions of black carbon emissions to slow down global warming (Hansen et al., 2000; Schellnhuber, 2008; Jacobson, 2010). However, some of these studies did not sufficiently consider the interaction of Kyoto gas emissions and aerosol emissions or between different aerosol species. This requires a detailed model, which we made use of.

In our study we investigate the impact of different evolution pathways of aerosol emission factors on short- and long-term climate. These scenarios can be interpreted as different stringencies of air pollution policies, which independently target large-scale and small-scale sources. We find that air pollution policies can reduce pollutant emissions substantially in the absence of climate policy. With a stringent global climate policy emissions are already reduced, which leads to a smaller additional impact of air pollution policies. These synergies between climate policy and air pollution policies have been described by many studies before and are confirmed in our work.

Contrary to previous studies, we did not find a significant impact of air pollution policies on long-term climate targets. Since climate policy leads to a strong decrease of fossil fuel use, even aerosol emission factors fixed to 2005 levels cannot yield sufficient SO_2 emission levels that would have a significant impact on 2100 or peak temperature. Therefore we find no conflict of interests between air pollution policies and climate policy. In scenarios without climate policies, impacts of different air pollution policies on aerosol emissions, and therefore also on the climate, are higher. Still we only find deviations in the range of tenths of degrees Celsius in global mean temperature.

In scenarios with climate policy, Kyoto forcing is reduced substantially compared to baseline scenarios. The associated reduction of aerosol forcing offsets a fraction of the reduction of Kyoto forcing, but does not overcompensate. To what extent the reduction in Kyoto forcing is offset depends on the stringency of air pollution policies.

As opposed to long-term climate, short-term temperature change may be affected by the design of air pollution policy. Independently of climate policy, air pollution policies are able to accelerate or decelerate global mean temperature change in the first decades. Without climate policy, the rate of temperature change increases throughout the first half of the century up to around 0.4 °C per decade. A weak air pollution policy decreases the rate of temperature change in the first two decades by up to 0.08 °C per decade, but has no effect on the long-term increase. With a stringent climate mitigation policy, the rate of temperature change starts declining before 2020 and approaches zero in the middle of the century. From 2025 on, there is very little difference between the air pollution policy scenarios and their rate of temperature change stays below all of the scenarios without climate policy.

Our findings show that the stringency of air pollution policies does not significantly affect the magnitude of the climate mitigation challenge. Thus, there is no trade-off between clean air and climate policies, as suggested by previous studies. To the contrary, our results confirm that climate policies induce substantial co-benefits to air pollution policies, by driving down fossil fuel use. While air pollution, both from carbonaceous aerosols and from sulfur, is harmful for humans and ecosystems, even stringent air pollution policies have almost no influence on medium- and long-term climate targets.

We conclude that the focus of climate mitigation efforts should therefore remain on the reduction of long-lived greenhouse gases. Our results confirm the synergies between air pollution policies and climate policies found in previous studies (Bollen et al., 2010; Riahi et al., 2012; van Vliet et al., 2012; McCollum et al., 2013). Furthermore, we show that there is no conflict of objectives between these two policies. These results suggest that air pollution policies can be implemented without negative interference with climate policy.

Summary of major findings

- Historically, economic development implied increasing energy demand
- Current integrated assessment models allocate very low final energy levels to developing countries if climate policies are in place
- Models may overestimate the potential for energy intensity reductions in developing countries
- This is a possible source of uncertainty for emission scenarios
- The choice of metric determines medium term CH_4 emission levels and the global emissions budget
- Global costs are only weakly affected by alternative metrics
- There is a trade-off between global costs and transient climate change
- Alternative metrics may lead to regional redistributions due to trade effects of fossil fuels and shifts in emissions permit trade
- GWP100 performs well in terms of global costs despite its simplicity
- Bioenergy is predominantly used to produce liquid fuels
- The value of bioenergy is determined by both its energy value and the value of negative emissions
- Tightening the climate target or restricting the bioenergy potential increases the deployment of technologies with higher capture rates
- BECCS can be a crucial mitigation option with high deployment levels and a high technology value, particularly for low stabilization targets
- Due to the creation of negative emissions, more biomass use allows for higher deployment of fossil energy for a given climate target
- Prolonged deployment of fossil fuels with the expectation of negative emissions could be a risky strategy, since both biomass potential and the availability of CCS are uncertain
- High demand and willingness-to-pay for biomass under a stringent climate target would be increased if emission reductions were postponed. This could increase pressure on the agricultural sector.
- Air pollution policies can reduce pollutant emissions substantially in the absence of climate policies. With stringent global climate policies, emissions are already reduced, which leads to a smaller additional impact of air pollution policies
- Air pollution policies do not affect long-term climate targets

- Simultaneous reduction of aerosols counteracts a fraction of the reduction of Kyoto forcing, but does not overcompensate
- Air pollution policies may affect short-term climate
- There is no trade-off between clean air and climate policies, but there are co-benefits for clean air from climate policies

7.2 Discussion and policy implications

To prevent dangerous anthropogenic interference with the climate, CO_2 has to be reduced substantially. Yet some residual emissions will be hard to avoid. Especially for developing countries it could be difficult to sustain their economic growth while at the same time reducing CO_2 emissions. In the context of sustainability, energy access is of importance as well. Historical patterns show that from a certain threshold on, when energy needs go beyond basic domestic demand, economic development goes along with energy demand. As of today, it is not clear how this pattern can be avoided, since energy is needed e.g. for building and maintaining infrastructure. Integrated assessment models have been relatively optimistic regarding the final energy demand of developing countries if climate policies are pursued. This indicates that these models may underestimate the energy demand of developing nations. When trying to determine emissions budgets, this possible source of emissions has to be taken into account. In the REMIND model, the energy demand assumptions were recently adjusted to reflect our findings. Final energy demand now reaches higher levels in developing countries also in case of stringent climate policies.
To achieve low stabilization scenarios, reducing CO_2 alone will likely not be sufficient. Non-CO_2Kyoto gases contribute substantially to today's radiative forcing, and will play a more and more important role as CO_2 is reduced. A number of studies, e.g. EMF21, have shown that economic costs for achieving a given climate target are considerably lower in a multi-gas approach. As of today, non-CO_2 greenhouse gases are included in the Kyoto protocol, but not in the European emissions trading scheme EU-ETS. Including non-CO_2 gases like CH_4 and N_2O e.g. in an emissions trading scheme raises two questions: First, how should they be included technically? In the Kyoto protocol, 100-year global warming potentials (GWP100) were used to convert non-CO_2 gases to CO_2 equivalents. In the meantime, the GWP100 has been challenged on economical and physical grounds. From a physics point of view, the time horizon is arbitrary and could be either chosen differently or the metric could depend on the proximity of the climate target instead of being time-invariant. A time-dependent metric using temperature instead of radiative forcing as a climate indicator has been proposed by Shine et al. (2005, 2007). Economists have argued that climate damages rather than physical climate variables are the appropriate indicator (Kandlikar, 1996). In our analysis we found that the choice of metric has little impact on global costs, but may lead to regional or sectoral redistributions. Since the GWP100 performs reasonably well, resources needed to negotiate a new metric could be used more efficiently in other areas. The second question concerns the framework of measuring and evaluating greenhouse gases. A large share of CH_4 and N_2O emissions arise in the agricultural sector, where emissions might be more difficult to measure. Judging from today's knowledge, abatement options in

this sector are limited. If a large share of residual emissions came from the agricultural sector, high emissions prices could have implications for food security.

The agricultural sector may not only face pressure from high emissions prices, but also from high demand for bioenergy. Bioenergy is a versatile energy carrier. It can be used to generate low-carbon fuels, which are one of the rare options to decarbonize the transport sector. In combination with carbon capture and storage (BECCS), bioenergy can generate negative CO_2 emissions. BECCS has been shown to be a very valuable mitigation option (e.g. EMF27), making low stabilization targets achievable at much lower costs. This high option value leads to a high willingness-to-pay for bioenergy, which could generate high revenues for bioenergy producers. This could increase pressure on the agricultural sector and have implications for food security, biodiversity, water management, fertilizer use, etc.

These considerations show that even though climate protection is an important issue, there are other sustainability issues that are important as well and are closely interlinked. Another important issue is air pollution. Sulfur emissions have negative impacts on human health and ecosystems, and millions of premature deaths every year are attributed to indoor pollution. Both indoor and outdoor pollution are largely due to aerosols. Overall, aerosols have a cooling effect on the climate. Therefore some studies suggested that stringent air pollution policies could accelerate global warming and make ambitious climate target harder to reach or even unachievable. In our study we found that air pollution policies are not able to influence long-term climate. Thus we concluded that there is no conflict of interest between air pollution policies and climate policies.

7.3 Outlook

In this thesis, we analyzed challenges to the achievement low stabilization scenarios, especially in terms of non-CO_2 emissions. There are a variety of directions where this research ought to be deepened or extended.

In Chapter 3 we analyzed integrated assessment model results with respect to final energy levels in developing countries. We found that there is a significant difference between historic relations between energy consumption and affluence and model results. Our analysis suggests that energy demand structures need to be represented more explicitly. Analyzing energy needs at different stages of development could prove to be a promising area of future research. More thorough bottom-up analyses regarding the relation of energy demand and wealth would be helpful in determining energy threshold levels that ought to be achieved in all regions.

In Chapter 4, we found that global economic costs can in some cases depend on CH_4 abatement measures. If further, even more expensive, mitigation options were available, this would increase headroom for CO_2 emissions and therefore decrease global costs. So far, there is only little information available as to what these mitigation options might look like and how costly they would be. Furthermore, it is unclear how fast abatement options could be implemented and whether there are challenges other than monetary that ought to be taken into account. Our modeling framework did not include agricultural markets explicitly. Yet since the agricultural sector is responsible for a large share of CH_4 and N_2O emissions, we expect that the choice of metric might influence these markets, especially if permit trade is considered. Further research on regional implications of the choice of metric would be desirable. In our model, we were only able to analyze eleven world regions. Our results should be tested by other models with different regional resolution or even by single country studies.

Results in Chapter 5 were based on assumptions on bioenergy supply and CCS availability and costs, which are all uncertain. Further research in these areas is absolutely necessary to gain more robust results. This research should not only comprise technical possibilities, but also social acceptance, risks, and risk management. In case of bioenergy, this is strongly connected with possible unintended side effects. Connecting the agricultural market with energy and carbon markets could lead to competition of bioenergy with food production and reduction of biodiversity. Especially implications of competition with food production are crucial and need to be understood better.

A big challenge when modeling aerosol emissions is uncertainty. Starting at the level of emissions, especially BC and OC data is scarce and lacks regional and sectoral detail. Emission characteristics can vary from source to source, which makes it hard to determine generalized emission factors. Therefore it would be even more important to have more reliable and detailed data. Another source of uncertainty is the conversion from emissions to radiative forcing. Atmospheric processes are not well enough understood so far to allow for more precise values. Further research in this area would be very valuable to decrease uncertainty. On the impact side, we only analyzed global effects on the climate. Due to the short lifetime of aerosols in the atmosphere, they do not mix very well, leading to more local than global effects. An analysis of local effects would require higher spacial resolution of emission sources as well as a higher resolution in the climate model. We found that air pollution policies might have an influence on the rate of temperature change in the next decades. Yet there is little research so far on the impacts of this rate of temperature change. It might influence adaptation of ecosystems, but there is little information e.g. on the extent of biodiversity loss caused by accelerated temperature change.

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Nomenclature

AR4	Fourth assessment report of the IPCC
BASE	Baseline scenario without climate policy
BAU	Baseline scenario without climate policy
BC	Black Carbon
BECCS	Bioenergy with Carbon Capture and Storage
BMBF	German Federal Ministry of Education and Research
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
EF	Emission Factor
EMF	Energy Modeling Forum
ERF	Efficient Radiative Forcing
F-gases	Fluorinated gases
GCP	Global Cost Potential
GHG	Greenhouse Gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
HDI	Human Development Index
HFCs	Hydrofluorocarbons
IAM	Integrated Assessment Model
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse-Response Function
MAC	Marginal Abatement Costs
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MDG	Millenium Development Goals
NIR	National Inventory Report
OC	Organic Carbon
OECD	Organization for Economic Cooperation and Development
PFCs	Perfluorocarbons
POL	Scenario with climate policy
PPP	Purchasing Power Parity
RCP	Representative Concentration Pathways
REMIND	Refined Model of Investment and technological Development
RF	Radiative Forcing
SAR	Second Assessment Report of the IPCC
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
SSP	Shared Socio-economic Pathways

TAR	Third Assessment Report of the IPCC
TCRE	Transient Climate Response to cumulative carbon Emissions
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change

Statement of Contribution

The five core chapters of this thesis (chapters 3 to 6) are the result of collaborations in this PhD project between the author of this thesis and her advisors and colleagues. The author of this thesis has made extensive contributions to the contents of all four papers, from conceptual design and technical development to writing.
This section details the contributions of the author to the four papers and acknowledges major contributions from others.

Chapter 3: Jan Steckel developed the principle research question and conceptual design of the paper. Jan Steckel also performed the data analysis of model results. Jan Steckel wrote the paper, with input from the author of this thesis. Robert J. Brecha contributed to parts of the introduction, discussion as well as to the statistical analysis of final energy consumption and economic development (section 2.1). Robert J. Brecha assisted with the conceptual design of the paper and performed parts of the statistical analysis in 2.1. The author, Jan Steckel and Michael Jakob performed the econometric analysis in sections 2.2 and 3.2. Gunnar Luderer gave substantial advice to the mansuscript, with respect to the modeling comparison efforts and provided the ReMIND-R scenarios.

Chapter 4: This chapter uses the REMIND model which has been developed at PIK. The author implemented a much more detailed representation of CH_4 and N_2O emissions, including a refined version of marginal abatement cost curves, and CO_2 emissions from cement production. Gunnar Luderer and Elmar Kriegler provided guidance and helpful input for the implementation. The author is responsible for the conceptual design of this paper, with input from Gunnar Luderer and Elmar Kriegler. The author performed the model runs, analyzed the data, and wrote the paper, with extensive revisions by Gunnar Luderer. Tino Aboumahboub and Gunnar Luderer devloped the decomposition method for regional costs. Tino Aboumahboub implemented this method in MATLAB.

Chapter 5: This chapter uses the REMIND model which has been developed at PIK. The author implemented a much more detailed representation of CH_4 and $\mathrm{N}_2\mathrm{O}$ emissions, including a refined version of marginal abatement cost curves, and CO_2 emissions from cement production and of aerosol emissions. David Klein and the author jointly performed the model runs. David Klein wrote the paper, with input by Nico Bauer, Alexander Popp, and the author. All co-authors contributed to paper revisions.

Chapter 6: This chapter uses the REMIND model which has been developed at

PIK. The author implemented the representation of the aerosol species SO_2, BC, and OC. Elmar Kriegler and Gunnar Luderer provided guidance and helpful input for the implementation. The author is responsible for the conceptual design of this paper, with input from Gunnar Luderer and Elmar Kriegler. The author performed the model runs, analyzed the data, and wrote the paper, with extensive revisions by Gunnar Luderer. Malte Meinshausen developed MAGICC, especially the probabilistic version.

Tools and Resources

This dissertation relies heavily on numerical modeling. Naturally, a number of software tools were used to create and run the models, and to process, analyze and visualize the results. This section lists these tools.

Modeling The REMIND model was implemented in GAMS[1]. The CONOPT3[2] solver was used to solve the non-linear formulations. All code projects were managed using the Subversion version control system[3].

Data Processing The MathWorks' MATLAB[4], version 7.5 (R2007b) was used for all data pre- and postprocessing work. The MATLAB Curve Fitting Toolbox was used to provide fits for MACs.

Typesetting This document was prepared using LaTeX 2ε[5], particularly the pdfpages package to include Chapters 3 to 6 in their given layouts. Zotero[6] was used for literature management.

Literature management Zotero was used for literature management and providing the bibliography to LaTeX 2ε and biblatex.

[1] http://www.gams.com
[2] http://www.gams.com/docs/conopt3.pdf
[3] http://subversion.apache.org/
[4] http://www.mathworks.de/products/matlab/
[5] http://www.latex-project.org/intro.html
[6] http://www.zotero.org/

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