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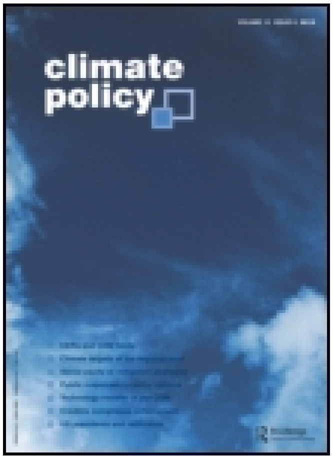

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Deep CO_2 emission reductions in a global bottom-up model approach

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climate policy

Deep CO_2 emission reductions in a global bottom-up model approach

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Most studies that explore deep GHG emission reduction scenarios assume that climate goals are reached by implementing least-cost emission mitigation options, typically by implementing a global carbon tax. Although such a method provides insight into total mitigation costs, it does not provide much information about how to achieve a transition towards a low-carbon energy system, which is of critical importance to achieving ambitious climate targets. To enable sensible deep emission reduction strategies, this study analysed the effectiveness of 16 specific mitigation measures on a global level up to 2050, by using an energy-system simulation model called TIMER. The measures range from specific energy efficiency measures, like banning traditional light bulbs and subsidizing electric vehicles, to broader policies like introducing a carbon tax in the electricity sector. All measures combined lead to global CO_2 emission reductions ranging between 39% and 73% compared to baseline by 2050, depending on the inclusion of sectoral carbon taxes and the availability of carbon capture and storage (CCS) and nuclear power. Although the effectiveness of the measures differs largely across regions, this study indicates that measures aimed at stimulating low-carbon electricity production result in the highest reductions in all regions.

Policy relevance

The results of the calculations can be used to evaluate the effects of individual climate change mitigation measures and identify priorities in discussions on global and regional policies. The type of fragmented policy scenarios presented here could provide a relevant bottom-up alternative to cost-optimal implementation of policies driven by a carbon tax. We identify overlapping and even counter-productive climate policy measures through an analysis that presents the policy effectiveness by region, and by sector. The set of 16 policy measures addresses the largest emitting sectors and represents options that are often discussed as part of planned policies.

Keywords: bottom-up; energy modelling; mitigation scenarios

1. Introduction

The scientific literature indicates that stringent GHG emission reductions are required to achieve the targets that are currently considered for internationally climate policy (e.g. the so-called 2 °C target). In the last few years the scientific community has started to explore such low-emission scenarios (Edenhofer, Knopf, Leimbach, & Bauer, 2010; van Vuuren et al., 2007, 2011). The great majority of scenarios in the literature looks at cases in which climate goals are achieved by least-cost emission

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mitigation options, implemented as a response to a universal price for GHG emissions, also known as a carbon tax.

In these scenarios, an ideal world with a global overarching climate policy framework is assumed. This ensures an optimal response to the carbon tax (sometimes referred to as a first-best world, see Staub-Kaminski, Zimmer, Jakob, & Marschinski, in press). Arguably, this is unrealistic, even more so in the short term, for several reasons. First, at present, international climate negotiations do not seem to be leading to an overarching climate agreement. The decisions in Copenhagen and Cancún have clearly led to a situation in which countries will participate in climate policy on a voluntary basis (pledges). More recently, in Durban, it was decided that a new global agreement will not take effect until 2020 (UNFCCC, 2012). Second, the mitigation strategies of governments, businesses, and households are often not only based on cost optimization, but also on other factors such as public support, infrastructure lock-in, visibility, and contribution to other policy goals. Moreover, factors such as inertia, lack of information, and institutional constraints play a role (Staub-Kaminski et al., in press). These factors might explain why, in several countries, financially attractive efficiency improvements are not being implemented, but other more costly technologies like photovoltaics are being deployed on an increasingly large scale (IEA, 2012), often supported by costly feed-in tariffs, as in Germany (Wand & Leuthold, 2011). This situation raises the question of whether it is possible in modelling exercises to account for non-optimality or for possible implementation barriers to reaching low emission scenarios.

Although most of the scenario literature seems to concentrate on optimal responses, literature on non-optimal climate responses does exist. For instance, Parry and Williams (1999) and Strachan and Usher (2012) have focused on the macro-economic effects of different policy types and targets, many of which were not optimal. Also in the scenario literature, non-optimal assumptions are being introduced gradually, for instance by focusing on the impact of reduced participation and non-optimal timing of emission reduction efforts (Clarke et al., 2009; Riahi et al., in press; van Vliet et al., 2012), or on the implications of the limited availability of certain technologies (Kriegler et al., 2014). However, except for the imposed restrictions, these studies still rely on cost minimization, hence providing – to some degree – ‘second-best’ solutions. An alternative approach is a bottom-up perspective, starting from what may be socially desirable as well as politically and technologically feasible. Such studies include comprehensive action plans and governmental strategies (for a recent meta-analysis, see Wiseman, Edwards & Luckins, 2013), but also studies that are commonly known as ‘wedge’ studies, which list very specific mitigation options and their theoretical emission reduction potential in relation to the 2 °C policy target (Blok, Hohne, van der Leun, & Harrison, 2012; Hoffert et al., 2002; Pacala & Socolow, 2004).

There are, however, two important limitations to these bottom-up studies. First, they are rarely expressed in the form of a comprehensive and quantified global scenario. For instance, of the 18 studies identified by Wiseman, only two fulfil this description, i.e. the study by Jacobson and Delucchi (2009, 2011) and the Ecofys Scenario (WWF international, 2011). These studies, and also the ‘wedge’ studies mentioned above, provide a bottom-up alternative to the cost-optimal climate policy scenarios. Although they arguably focus on relevant policy measures, these studies have difficulties in addressing the overlap and indirect effects that the individual changes in the (energy) system may have. For instance, policy measures may overlap in terms of potential reductions (if cars use carbon-neutral fuels, there is no climate effect of increased fuel efficiency), and changing energy prices may cause so-called rebound effects (less use of coal for one cause will probably make it a cheap fuel for other purposes).

Given these shortcomings in the existing literature, this study looks at the effectiveness of individual mitigation measures in a global energy system simulation model, thereby deviating from existing literature on both optimal and non-optimal mitigation responses. Through this model exercise, we aim to gain more insight into the contribution of specific mitigation measures to reaching global deep emission reductions by 2050. As the analysis is done within a single energy system simulation model, overlaps and trade-offs of sectoral policies in reaching ambitious global climate goals are identified. This article adds to the discussion on the different model approaches as framed by van Vuuren et al. (2009) and is based on research carried out within the European FP7 research project RESPONSES (Deetman, Hof, & van Vuuren, 2012).

The assessment explores the impacts of a selected set of mitigation options. The list of these options included in this study is not exhaustive, as it is not the intention of the study to analyse the feasibility of achieving the 2 °C target.

Section 2 starts by presenting the mitigation options included in this study by sector, and describes the model, assumptions, and method used to assess their effects. Section 3 then discusses the resulting CO_2 emission reduction potentials of each measure and the combination of measures. Section 4 concludes with a summary of the findings and a short discussion.

2. Method

2.1. Model description

The Targets IMage Energy Regional (TIMER) energy simulation model (van Vuuren, van Ruijven, Hoogwijk, Isaac, & de Vries, 2006) is used to assess the mitigation potential of 16 CO_2 mitigation options. TIMER has been used in various studies on global emission reduction measures (van Vuuren et al., 2011; van Vliet et al., 2009) and generates projections of a range of GHG emissions from energy-related activities.

TIMER describes long-term development pathways in the energy system in the broader context of impacts on climate change, air pollution, and sustainable development. It is an energy-system simulation model, describing the demand and supply of various energy carriers (such as coal, gas, oil, hydrogen, biomass, and electricity) and their transformation for 26 world regions on a yearly basis. The choice for the deployment of different energy technologies is based on their relative costs, through a multinomial logit function:

$$\mathrm{IS}_i = \frac{\mathrm{e}^{-\lambda c_i}}{\sum_{k=1}^{J} \mathrm{e}^{-\lambda c_k}}, \quad i = 1, \ldots, J,$$

where IS is the annual investment share for technology i, c is the overall cost in US dollars per unit of energy delivered (including investment and production costs as well as premiums and taxes), and λ is the so-called logit parameter, which is calibrated in accordance with historic market responses (van Vuuren et al., 2006). This allows us to assess the effects of policy interventions, like a carbon tax or a subsidy/feed-in-tariff. Furthermore, TIMER focuses particularly on several dynamic relationships within the energy system, such as inertia due to stock lifetimes, learning by doing, fuel depletion, and trade among the different regions, which makes it a particularly useful model with which to study the long-term development of the energy system. Final energy demand (for five sectors and multiple energy carriers) is modelled as a function of changes in population, economic activity, and structure of the sectors, assuming a regional intensity-of-use curve. Energy demand in some sectors is described in further detail by submodules on residential energy use (described by Daioglou, 2010), transport energy use (described by Girod, Vuuren, & Deetman, 2012), and heavy industry energy use (described by Boskaljon, 2010). Additional information on the essential dynamics and assumptions of the TIMER model can be found in the Supplementary Information.

2.2. Baseline scenario

The baseline scenario used throughout this study is described in the Organisation for Economic Co-operation and Development (OECD) Environmental Outlook 2012 (OECD, 2012), with the exception of the transport sector, which is represented by the detailed travel and freight transport model as described by Girod et al. (2012). The baseline assumptions on global development of population and gross domestic product (GDP) used in the Environmental Outlook are given in Table 1. The projections for GDP are in line with historic growth rates. Population assumptions are based on medium projections of the UN (UN, 2008). Projections for energy consumption in the baseline roughly follow the projections of the International Energy Agency (IEA) Energy Outlook (IEA, 2010) and are within the range found in the literature as reviewed by van Vuuren et al. (2012). Because the TIMER framework is a long-term global energy-use model, baseline projections generally do not include detailed assumptions on planned regional policies. Excluding these planned climate policies may lead to some overestimation of baseline emissions.

2.3. Description of mitigation options

In defining the mitigation options, we focus on the largest emitting sectors on a global scale, now and by 2050. Figure 1 shows the historic and projected baseline CO_2 emissions from energy use. The largest emitting sectors are the electricity, transport, industry, and residential sectors.

TABLE 1 Baseline assumptions on population and GDP up to 2050 for three world regions

	Region	2010	2020	2030	2040	2050
Population (millions)	OECD	1,184	1,235	1,267	1,282	1,283
	BRIICS	3,238	3,503	3,674	3,756	3,764
	Rest of the world	2,486	2,936	3,366	3,761	4,101
	Total population	6,908	7,674	8,307	8,799	9,148
GDP (billion US$$_{2010}$)	OECD	39,227	49,093	60,738	73,677	87,871
	BRIICS	24,420	45,513	70,891	103,822	141,179
	Rest of the world	13,569	20,790	32,650	50,597	75,712
	Total GDP	77,216	115,396	164,279	228,096	304,762

Note: BRIICS: Brazil, Russia, India, Indonesia, China, South Africa.

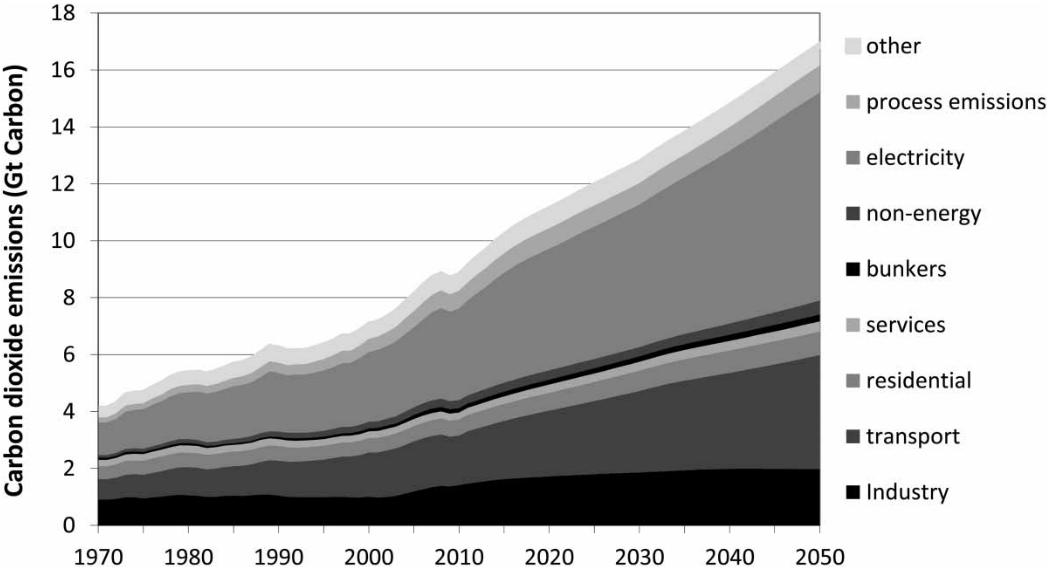

Figure 1 Global annual CO_2 emissions (baseline) from energy use.

The climate mitigation options analysed in this article are elaborated by sector in the following sections. Most options are policy instruments such as taxes, subsidies, bans, or enforcing minimum technology standards, but we also include some technical measures. Together, the measures closely resemble the six basic policy types as identified by Fischer and Newell (2008), these being an emissions price, an emission performance standard, a fossil fuel tax, a renewables share requirement, as subsidy on renewable energy, and a subsidy on research. They lead to different effects across regions due to differences in the current energy system and different assumptions on technological costs for both installations and fuel. The effects of the options do not ‘add up’ to any climate policy temperature target. They have been selected to illustrate what specific, ambitious options may achieve – and how they compare to the extensive emission reductions necessary to comply with the 2 °C target. They represent options that are often discussed as part of planned policies, but others are included for illustrative purposes. More details on the individual measures can be found in the Supplementary Information.

2.3.1. Power generation

1. *30% renewable electricity*

The first measure is a global target of 30% renewable electricity generation by 2050, by increasing the share of wind and solar. Given the potential negative impacts of bio-energy for biodiversity (Hellmann & Verburg, 2010; Teeffelen et al., 2011; van Vuuren, Bellevrat, Kitous, & Isaac, 2010), we assume no additional bio-energy use compared to the baseline. Even though some studies argue for a fully renewable energy system by 2050 (Jacobson & Delucchi, 2011), we recognize the concerns about the variability of renewable energy sources (Trainer, 2012) and choose a moderately conservative target. This target comprises a doubling of the renewable deployment compared to our model baseline by 2050, in which about 6% of global electricity is generated by biomass and about 9% by solar and wind as a result of cost assumptions derived from Hoogwijk (2004). The gap to the 30% target is closed by an allocation of 80% to additional wind and 20% to solar for every region. This roughly resembles global production ratios by 2010 according to REN21 (2011).

2. *Global carbon tax in the electricity sector*
In the low emission scenario for the OECD Environmental Outlook (called the 450 Core Scenario in the Outlook), reaching a 2 °C climate target in the long term is achieved by applying a global carbon tax, starting from 2013 and increasing over time to US\$110/tCO_2 in 2050 (OECD, 2012). In this study, we apply the same carbon tax path (see Supplementary Information), but only to the electricity generation sector. We apply such a carbon tax in two alternative settings, as a policy option with and one without additional carbon capture and storage (CCS) and nuclear, as described under items 2a and 2b.

2a. *Option without additional CCS and nuclear*
The expansion of nuclear power generation capacity has become even more controversial in some countries since the Fukushima nuclear disaster (Schneider, 2011), and the potential for large-scale deployment of CCS technologies remains unclear, mostly because of lack of societal and policy support (Bäckstrand, Meadowcroft, & Oppenheimer, 2011; Gough, Mander, & Haszeldine, 2010). Therefore, we include the results for the policy option to exclude additional use of these technologies from 2011 onwards. The existing nuclear plants will continue to operate over their economic lifetime of 45 years.

2b. *Option with additional CCS and nuclear*
In this policy option, expansion of nuclear power generation and CCS technologies is allowed under the presumption that an exclusion of these technologies could increase climate policy costs substantially (van Vliet et al., 2013). Comparison with the 2a scenario provides insight into the potential contribution of these technologies for reducing GHG emissions.

3. *Gradual ban on coal-fired power plants*
Kharecha and Hansen (2008) proposed the phase-out of coal-fired power plants without sequestration before mid-century as a feasible option to keep the atmospheric CO_2 concentration from exceeding about 450 ppm by 2100. To assess the effects of such a phase-out, we assume that the construction of new coal-fired power plants without CCS is banned in Annex I regions from 2012 onwards. For other regions, we assume that the ban will be implemented from 2021 onwards.

2.3.2. Road transport

4. *Global fuel tax and subsidy of plug-in/hybrid cars*
This measure consists of a combination of (1) a tax on fossil fuels in the transport sector and (2) a subsidy on the purchase price of plug-in/hybrid electric vehicles (PHEVs). PHEVs use about a third of the fuel compared to an internal combustion car, and have an additional electricity consumption of

0.13 MJ per passenger kilometre (Girod et al., 2012). The fuel tax aims to lower CO_2 emissions in all types of transport (including freight), while the subsidy on PHEVs only affects the CO_2 emissions of passenger cars, which are the largest contributor to passenger transportation emissions. The level of the tax is 25% of the current average Western European taxes on fossil gas and oil use and is gradually added to the existing taxes in all regions between 2015 and 2030. This corresponds to $0.19/litre of gasoline and diesel and $0.11/litre of liquefied petroleum gas (LPG) by 2030. For each region, the subsidy on PHEVs is set at a level so that the vehicle share is 50% by 2050 (see Supplementary Information). At a global level, the income and expenses roughly balance each other, so the measure could be seen as a dedicated tax and subsidy system.

5. *Biofuel standards in transport*

In 2009, the EU announced a new target of 10% biofuel blending by 2020 for transport fuels (European Commission, 2009a). Based on this measure, we included a global biofuel blending standard that increases from 5.75% in 2010 (European Commission, 2003) to 10% in 2020 and 30% by 2050. Biofuel blending targets for gasoline cars of between 10% and 20% would be achievable without changes to the vehicles' engines, and higher targets could be achieved by relying on flexible fuel vehicles (with adjusted engines, allowing for blending up to 85%) or biodiesel, which is fully compatible with existing vehicle and distribution infrastructure (IEA, 2011). It should be noted, however, that, for the sake of simplicity and transparency in this model exercise, we assume biofuels to be carbon-neutral, which is a disputed topic (see, e.g. DeCicco, 2013).

6. *CAFE fuel efficiency standards*

The US plans to implement Corporate Average Fuel Economy (CAFE) standards (EPA & NHTSA, 2012). These standards prescribe an increasing fuel efficiency for cars and light trucks from 35 to 54.5 miles per gallon between 2016 and 2025. This means that cars that do not fulfil these requirements will no longer be allowed to be sold in the US. More efficient fossil-fuelled cars are made available as an alternative, but at a higher purchase price (of $950 per car in 2016 and $2900 per car by 2025). We simulate the introduction of these CAFE standards for both passenger transportation and freight (truck) transport in all regions. For details, see the Supplementary Information.

7. *Subsidizing high-speed trains and taxing air travel*

Air travel is one of the fastest growing modes of transport in Europe (Eurostat, 2012) and many other regions. Replacing air travel with high-speed train (HST) travel could be an effective way to mitigate GHG emissions, as HST involves lower carbon emissions per passenger kilometre, and is at least partly capable of transport over similar distances. We keep traveller preferences based on time and budget considerations similar to the settings described by Girod et al. (2012) and model the implementation of the following options aimed at increasing the modal split of HST at the cost of air travel:

- A tax on air travel of almost $0.02/km, gradually implemented from 2015 to 2030;
- A gradual introduction of a subsidy on HST transport, starting in 2015 and reaching a level corresponding to 25% of the capital investments by 2030;
- An increase of HST door-to-door speed from 150 km/h by 2005 to almost 175 km/h by 2050 compared to a constant 2005 speed in the baseline.

2.3.3. Residential

8. *Tax of \$100/tCO$_2$ on residential energy use*

This option consists of a global carbon tax in the residential sector at a constant \$100/tCO$_2$ from 2015 onwards. This option is mainly chosen to analyse its potential effect.

9. *Gradual ban on incandescent light bulbs*

The EU endorsed the phase-out of incandescent lamps between 2009 and 2012 (European Commission, 2009b), prohibiting sales after September 2012. In this study, we simulate an instantaneous global ban on the sales of incandescent light bulbs from 2012 onwards. The light bulbs are replaced with advanced lighting options, consisting of a mix of compact fluorescent lighting (CFL) and light-emitting diodes (LEDs).

10. *Advanced heating and insulation technologies*

Globally, residential energy use accounts for 27% of the total energy demand. Just over 40% of residential energy is used for space and water heating. To explore the effects of more efficient residential heating, we model a gradual installation of (1) advanced insulation and (2) a 10% increase in efficiency of heating devices for cooking water, in newly built houses between 2015 and 2030.

Based on the best available technologies specified by Graus, Blomen, Kleßmann, Capone, and Stricker (2009) and Graus, Blomen, and Worrell (2011), we derived the lowest possible value of total energy consumption, 15 kJ per square metre of living space per heating degree day (HDD, as applied by Isaac & van Vuuren, 2009). We assume a gradual implementation of this standard for newly built houses from 2015 until 2030, and account both for lower cooking energy demand as well as lower heating and cooling demand, as elaborated in the Supplementary Information.

11. *One m^2 solar photovoltaics (PV) panel for every household in the world*

We simulate the installation of 1 m^2 of typical crystalline silicon PV panel on the rooftop of every household between 2015 and 2030, which (at a global average household size of 2.7 persons by 2050) is less than the 2–3 m^2 per person proposed by Pacala and Socolow (2004). We choose to provide results per m^2, but emphasize that the installation of PV surfaces under 10 m^2 per person would still be in accordance with observations on the availability of roof space according to Izquierdo, Rodrigues, and Fueyo (2008). We use an overall conversion efficiency of 10.8% and assume that all generated solar electricity is either directly used or fed back to the grid, so the generated electricity is directly subtracted from the residential energy use.

12. *Enforcing 'A' label appliances*

We assume that, globally, the average newly purchased appliance (with an average 15-year lifespan) currently has a 'C' energy label, based on the European energy labelling directive (European Commission, 2010). The global enforcement of sales of 'A' label appliances is modelled by assuming a decrease in the energy use of dishwashers of 27%, of refrigerators (A++) by 67%, of tumbler driers by 48%, of laundry machines by 29%, of televisions by 52%, and of air conditioners by 24%, all between 2015 and 2030.

2.3.4. Industry

13. *Tax of \$100/tCO_2 on industrial energy use*
This option consists of a \$100/tCO_2 carbon tax in the industrial sector, levied from 2015 onwards. This is included to compare the results with the same carbon tax in the residential sector.

14. *Standards for clinker ratios and carbon capture for cement*
Clinker, the main ingredient of cement, can be partially replaced by other materials (some available as waste streams such as fly ash or blast furnace slag), leading to a lower demand for clinker per tonne of cement (Taylor, Tam, & Gielen, 2006). As clinker is an energy- and CO_2-intensive intermediate, maximum standards for clinker ratios could mitigate emissions in cement production. We set the maximum standard at 65% by 2030, decreasing linearly from 2015 levels. As a result of introducing this maximum standard, clinker demand for cement production would decrease by about 12% below baseline levels by 2050.

In addition, we model the gradual phase-out of inefficient cement plants between 2015 and 2030, by only allowing more advanced cement plants to be built (which are about 25% more efficient than the typical one). Also, the efficiency of oxy-fuelled CO_2 capture technologies is increased from 55% to 75%, which could be achieved by synergetic by-product use of captured CO_2 and gypsum (Deetman et al., 2011). This last assumption will only have an effect when combined with a carbon tax in the industrial sector (measure 12), as CCS is not deployed without such tax.

15. *Enforcing 'good housekeeping' measures*
Energy efficiency improvements in industry do not always comprise radical changes in production processes. Sensible minor adjustments can typically enable energy savings on the order of 10–20% (Worrell, Bernstein, Roy, Price, & Harnisch, 2009). Examples of so-called 'good housekeeping' measures are using efficient lighting (and lighting management), more efficient and flexibly adjustable motors, optimized compressed air systems (Kaya, Phelan, Chau, & Ibrahim Sarac, 2002), and more preventive maintenance. In this study, we simulate the effect of a gradual adoption of such good housekeeping measures in the industry sector between 2015 and 2030, leading to a region-dependent efficiency improvement between 3.5 and 15% (see Supplementary Information).

16. *Enforcing advanced-type steel furnaces*
Smelting of iron ore and production of steel are very energy-intensive processes, and energy use for steel production is projected to increase by about 50% globally between 2010 and 2050. Steel production from scrap metal in electric-arc furnaces (currently considered to be the most energy-efficient option) is limited by the availability of scrap metal (Neelis & Patel, 2006). Thus, we enforce all newly built steel furnaces to be of the most efficient steel blast furnaces type (with or without CCS) from 2015 onwards.

3. Results

3.1. Effects of individual measures

Figure 2 shows the projected effect on CO_2 emissions of each of the measures introduced in Section 2, excluding, for now, the carbon tax in the electricity sector (see Section 3.2). The figure shows global

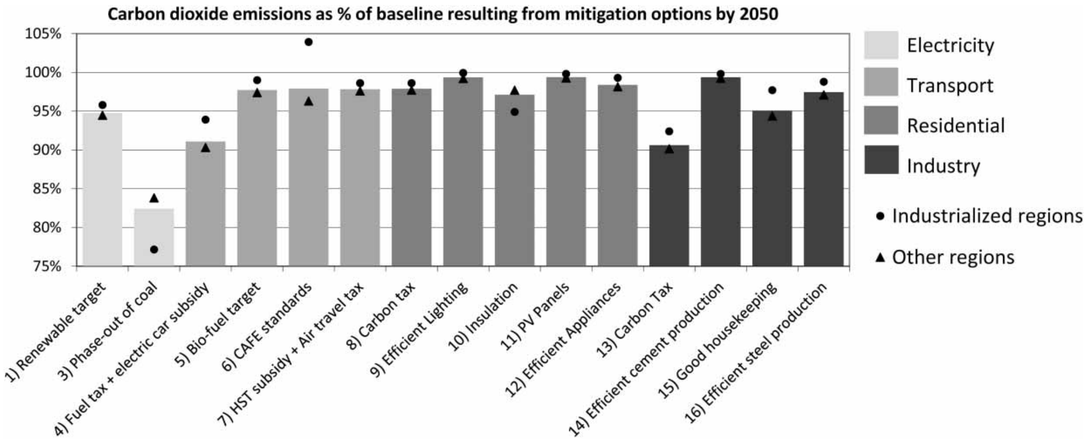

Figure 2 CO_2 emissions resulting from individual mitigation options as % of baseline energy-related CO_2 emissions by 2050.

reductions compared to the baseline scenario, as well as the reductions for industrialized and developing regions. In most cases, larger reductions are projected for developing regions than for industrialized regions. This is because they have higher absolute emissions by 2050 and lower efficiency levels in the baseline.

The most effective single measure considered here is the gradual ban on building coal-fired power plants, which is projected to reduce emissions by about 18% globally and by more than 20% in developed countries. Phasing out coal is one of the few measures that leads to higher CO_2 reductions in industrialized regions than in developing regions. This is a result of the assumed timing, the high share of electricity use in industrialized regions, and a relatively high share of coal in their generation capacity.

Another observation is that advanced residential insulation brings about a higher reduction in industrialized regions than in developing regions. The reason for this is that heating has a smaller share in total residential energy use in developing regions than in developed regions.

Most options examined only involve a small share of total emissions, and consequently also lead to global emission reductions of 3% or less. Typical examples are the ban on light bulbs, the installation of 1 m^2 of PV panels on every household, and maximum standards for clinker ratios in the cement industry. Exceptions are the renewable target in the power generation sector (5% reduction), fuel tax in combination with a subsidy on electric vehicles (9% reduction), a carbon tax, and good housekeeping measures for the industry sector (9% and 5% reductions, respectively). The effects of a carbon tax in the electricity sector were not included in Figure 2 to better compare the other measures with each other. Figure 3 does include the effects of the carbon tax in the electricity sector (measures 2a and 2b).

The results in Figure 2 only show the effect of the simulated measures by 2050. If low-carbon technologies are already partially adopted in the baseline, as is the case in some regions for efficient lighting and efficient steel and cement production, the simulated measures only speed up the transition. By 2050, the effect of the measures may thus seem limited, while the effect on cumulative CO_2 reductions in the period between 2010 and 2050 may be higher.

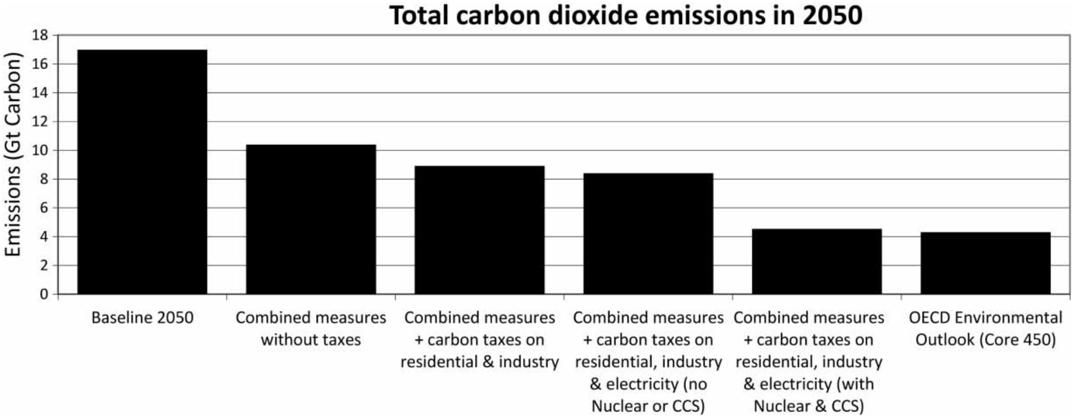

Figure 3 Total global CO_2 emissions in the baseline by 2050 and for four selected sets of mitigation measures, compared to the OECD 450 Core scenario (OECD, 2012).

The results are rather counter-intuitive for global implementation of fuel efficiency standards for passenger cars, like the CAFE standards in the US. Even though the CAFE standards would lead to a reduction of global CO_2 emissions by 2050, emissions in industrialized regions could increase as a result of this measure. The reason for this is that the CAFE standards may lead to fossil-fuelled car types with lower prices per kilometre. As a result, cheap fossil-fuelled cars push the large-scale adoption of electric and biofuelled cars ahead in time, or prevent electric vehicles from entering the market at all. This is the case for regions with a high level of affluence or high transport fuel taxes, like the US, Europe, and Oceania. These findings indicate that fuel efficiency standards could be effective in some regions, but may be counterproductive in other regions in the long term – especially if combined with other stringent climate policies. However, the CAFE standards do lead to cumulative emission reductions between 2010 and 2050, both in industrialized and other regions. This is because the short-term emission savings from fuel efficiency compensate for the long-term additional emissions from market developments over this period.

3.2. Combined effects

Obviously, the total reduction of all options combined is smaller than the sum of the reductions of individual options. Overlaps include the linkages between supply and demand of energy, and also specific measures such as a fossil-fuel tax and biofuel blending target, which both stimulate a higher share of bio-fuelled cars. We provide an overview of the total global emission reductions for different combinations of measures in Figure 3. It should be emphasized again that the list of options included in the analysis is rather arbitrary; the results should only be interpreted as indicative of the level of emission reduction that can be achieved by a well-defined set of reduction measures.

The total global CO_2 emission reductions compared to the baseline in 2050 range between 39% and 73%, depending on the inclusion of sectoral carbon taxes and the availability of CCS and nuclear power. For comparison, the OECD 450 Core emission pathway requires a 75% reduction compared to baseline in order to achieve a likely chance of meeting the 2 °C target.

As emphasized in other studies, the electricity sector is shown to have a pivotal role in reaching a 2 °C pathway. The electricity sector is responsible for a very high and rapidly increasing share of global emissions under baseline conditions, and several alternatives exists to significantly reduce them. Here, we have shown the impact of a ban on coal-fired power plants, a renewable energy target, and a sectoral carbon tax. The results in Figure 3 show that the availability of nuclear and CCS technologies in the electricity sector contributes greatly to the emission reduction potential.

3.3. Analysis of reductions by sector and region

Figures 4–7 show regional overviews of the emission reductions by sector, to further explore regional differences in the results. Figure 4 clearly shows that a possible phase-out of coal also reduces the effectiveness of a renewable target. This is because the generation capacity that replaces the coal-fired plants would be partly based on renewable energy. A coal phase-out would be more effective than the 30% renewables target, because it promotes the production of renewable energy indirectly, but some regional differences exist. A coal phase-out is particularly effective in North America in our assessment, and has a relatively low effect in Latin America. This is mostly because, historically and in our baseline projection, North America has a high dependence on coal-based electricity. It should be noted that the recent developments with respect to unconventional natural gas in North America may, in fact, lead to different results for this region. In Latin America, coal-based power in any case plays a much smaller role.

The transport sector shows stronger regional differences between the outcomes of the modelled measures (Figure 5). The highest reductions are reached in Latin America and Africa, due to the existing fuel (in)efficiencies and the lower fuel tax levels. In all regions, the fuel tax combined with subsidies on electric vehicles contributes the largest part of the combined reductions, but other measures show a more heterogeneous effect. For example, introducing a biofuel target reduces transport emissions by

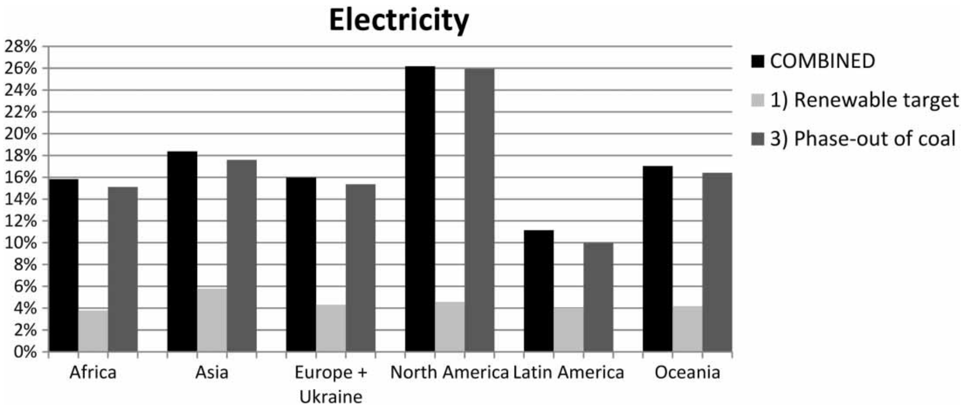

Figure 4 Regional emission reductions from measures in the electricity sector by 2050, compared to the reductions resulting from the combined measures.

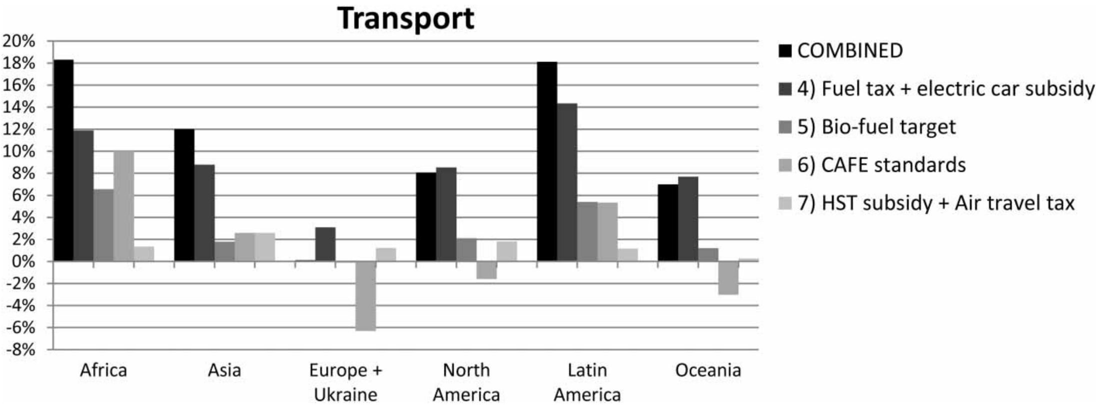

Figure 5 Regional emission reductions from measures in the transport sector by 2050, compared to the reductions resulting from the combined measures.

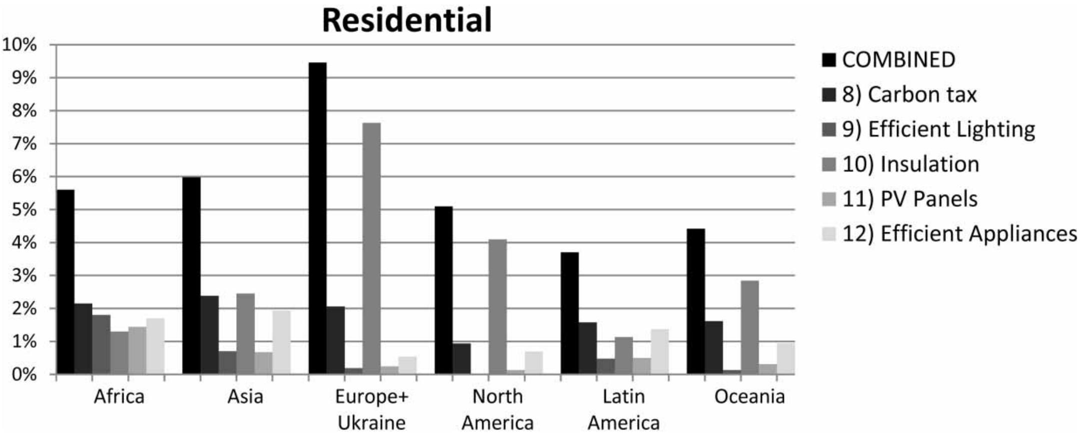

Figure 6 Regional emission reductions from measures in the residential sector by 2050, compared to the reductions resulting from the combined measures.

about 6% in Africa, but has negligible effects in the regions Europe + Ukraine and Oceania. As explained in Section 3.1, the global introduction of CAFE standards has an even more diverse effect across regions. In Europe in particular, the measure leads to additional emissions.

Figure 6 shows that insulation measures are particularly effective in regions that have a high space heating demand, like Europe and North America. By contrast, regions like Africa and Asia tend to have a high solar irradiance, and thus show the largest reductions when efficient appliances (air conditioners) or PV panels are implemented. In most regions, however, the effect of the PV panels and efficient lighting is limited because 1 m^2 per household is simply not enough to make a considerable contribution. Income effects are another explanation for regional differences between outcomes. The relatively high

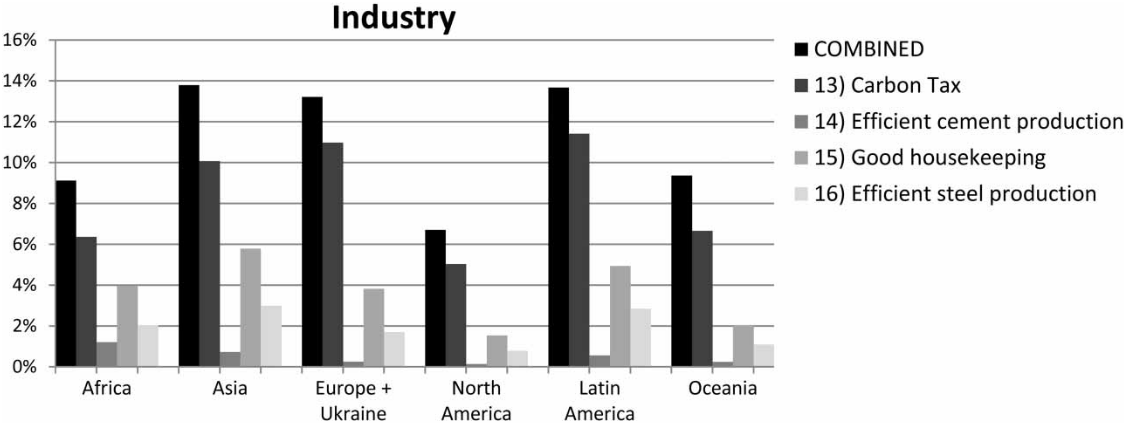

Figure 7 Regional emission reductions from measures in the industry sector by 2050, compared to the reductions resulting from the combined measures.

incomes in Europe and North America ensure that, in the baseline, incandescent light bulbs are already replaced by advanced lighting options, leaving barely any additional emission reduction potential from the ban of traditional bulbs. Moreover, lighting represents only a small share of the total power consumption.

The industrial efficiency measures have a relatively low effect on industrial emissions in regions such as North America (see Figure 7). This is mostly because the energy use for cement and steel production is small compared to the total industry in this region. The effects of increased efficiencies in steel and cement production are highest for Asia and Africa, respectively, because demand for these industrial products is expected to rise there.

The proposed measures only affect newly installed facilities, so they have a greater effect in regions that are expanding their production capacity. The regional differences in the results for good housekeeping measures can mostly be explained by the assumptions, which distinguish between the potential for developed and developing regions.

Overall, Figures 4–7 give an indication of the overlap between bottom-up mitigation measures when they are combined in comprehensive policy planning. Of the regional sets of measures shown, the observed overlap ranges between 8% for industry measures in Oceania, to over 60% for transport measures in Africa. Part of this overlap is clearly due to the overlapping potentials and definitions of the measures, which could be prevented by a smarter selection of measures; however, a considerable part of the overlap could be explained by price effects, which are not generally considered by ‘wedge’ studies or other typical bottom-up climate change mitigation strategies.

4. Discussion

Of the measures analysed, a global phase-out of coal-fired power plants had the largest effect on CO_2 emissions, reducing them by 18% by 2050. Other measures with a large effect are a carbon tax in the industry sector and the stimulation of electric vehicles. Other measures have only a small effect, as they are not stringent or only involve a small share of the emissions. Examples of such measures are increased efficiencies for cement production, the introduction of solar PV panels for every household, and the introduction of efficient lighting. The global reductions of each of these separate measures involve up to 1% of global emissions. The measures aimed at lighting and PV panels can lead to relatively high reductions in regions such as Africa and Asia. In general, regional differences can be attributed to historic development of the energy system, climatological circumstances, as well as income differences, and they are largest for measures in the residential and transport sectors. An illustrative example of regional differentiation in the transport sector is the implementation of CAFE (fuel efficiency) standards for passenger cars. The fuel efficiency standards cause a drop in CO_2 emissions in the short term, but by 2050 they lead to higher emissions in some regions. However, this outcome may be highly sensitive to the simplifications and assumptions made, because we exclude spill-over effects (for a short discussion, see the Supplementary Information). We emphasize that the current exercise is static in the sense that it uses predefined policy timing. A next step in such bottom-up model analysis could be focused on limiting policy overlap by adjusting the timing of technological measures in relation to carbon taxes, as their interaction is suggested to have an optimal timing aspect (Gerlagh, Kverndokk, & Rosendahl, 2009).

All measures combined, including carbon taxes in the electricity, residential, and industrial sectors, are expected to reduce the total energy-related CO_2 emissions by 73% relative to baseline by 2050, provided that additional nuclear energy and CCS technologies are available. This is close to the 75% reduction found in the cost-optimal 2 °C scenario of the OECD. This implies that the set of measures described in this article may indeed be seen as illustrative of ambition levels consistent with the 2 °C target. However, it should be noted that the list of measures described in this report is not exhaustive and was drafted based on the authors judgement, only to illustrate what a set of ambitious, but tangible climate action measures may look like. We should also add that by applying the measures as elaborated, our modelling framework does not allow us to derive overall climate change policy costs easily. This is an important aspect missing in the comparison with the 2 °C scenario of the OECD.

5. Conclusion

In this article, we have introduced a set of model calculations that consider specific GHG emission reduction measures that can be used as part of climate change mitigation policies. The calculations allow for an evaluation of these concrete and tangible policies, but we are unable to asses overall costs for climate policy. We argue that this type of fragmented policy scenario could still provide a relevant alternative to the cost-optimal implementation of policies driven by a carbon tax, because it recognizes societal barriers as well as political preferences for reduction measures. We conclude that it is possible to come up with a set of measures that achieves CO_2 emission levels close to an exemplary 2 °C scenario by 2050. However, for the electricity sector in particular this requires ambitious interventions, such as a coal phase-out and the use of carbon capture and storage (CCS) technologies. We would encourage other integrated assessment modelling groups to pursue experiments such as the one presented here, as this would enable a more explicit and robust formulation of climate policy's task in future.

The results of the calculations can be used to evaluate individual climate mitigation measures and determine priorities in discussions on global and regional policies. In some cases, it might be envisioned that global agreements on specific actions regarding these measures might facilitate the currently slow international climate negotiations. All in all, we conclude that the analysis of concrete emission reduction measures in a global energy system simulation model is a useful addition to current literature on economically optimal top-down response strategies and other bottom-up studies. One of the main reasons is that it allows us to explicitly assess the – sometimes substantial – overlap between measures, which is generally missing in both existing top-down and bottom-up climate change mitigation studies.

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Supplemental data

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