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Dissertation
38

Risks, costs and equity

Modelling efficient strategies for climate and energy policy

Tommi Ekholm

VTT SCIENCE 38

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Modelling efficient strategies for climate and energy policy

Tommi Ekholm

VTT Technical Research Centre of Finland

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Risks, costs and equity
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Riskit, kustannukset ja tasapuolisuus. Tehokkaiden strategioiden mallinnus ilmasto- ja energiapolitiikkaa varten. **Tommi Ekholm.** Espoo 2013. VTT Science 38. 30 p. + app. 80 p.

Abstract

The mitigation of climate change can be framed as a problem of risk management on a global scale. Avoiding dangerous interference with ecosystems and human society calls for a global climate policy, which will translate a selected climatic target into economic incentives for reducing greenhouse gas emissions.

The necessary emission reductions span many decades and involve actors at different levels of the global economy, from nations to companies and individuals. The reductions entail economic costs which are likely to be unevenly distributed across regions and individuals. Uncertainty in how the climate responds to increased greenhouse gas concentrations creates a risk in that the costs of attaining the selected target may increase. Furthermore, climate policy cannot be isolated from other policy aims; aims that can be contradictory to the aspirations of climate policy.

This Dissertation uses numerical scenario modelling to address these issues, and to aid the formulation of efficient climate and energy policies. The perspectives span from the global cost-efficiency analysis of attaining a predetermined temperature target to the consideration of regional equity in mitigation costs, and further to the modelling of capital scarcity and preferences in developing countries. The Articles in this Dissertation share a number of common questions, particularly how costs occurring at different times should be discounted into a single present value, and how the heterogeneity between different actors – regions, countries or households – should be taken into account in policy formulation.

On one hand, the results provide guidance on how the emissions of different greenhouse gases should be priced; and how a global emission market could be used to select the most cost-efficient mitigation measures and to distribute the costs in an equitable manner. On the other hand, the Articles also illustrate potential hindrances for achieving efficient and equitable outcomes. Both types of results share a common aim, which is to explore and quantify the impacts of possible policy options and to facilitate the development of more informed strategies and policies.

Keywords climate policy, energy policy, energy economics, scenario

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Tiivistelmä

Ilmastonmuutoksen hillintää voidaan ajatella globaalin mittakaavan riskienhallintakysymyksenä. Ilmastonmuutoksen ekosysteemeille ja yhteiskunnalle aiheuttaman uhan vähentämiseksi tarvitaan maailmanlaajuista ilmastopolitiikkaa, joka luo valittuja ilmastotavoitteita heijastavat taloudelliset kannustimet kasvihuonekaasupäästöjen vähentämiseksi.

Tarvittavia päästövähennyksiä tulee toteuttaa useiden vuosikymmenien aikana, ja ne koskevat toimijoita talouden eri tasoilla: valtioita, yrityksiä ja yksittäisiä ihmisiä. Päästövähennyksistä koituvat kustannukset jakautuvat epätasaisesti eri valtioiden välille. Epävarmuus ilmaston herkkyydestä kasvaville kasvihuonekaasupitoisuuksille ilmakehässä muodostaa riskin, että valittuihin ilmastotavoitteisiin pääseminen aiheuttaa kustannuksia, jotka ovat nykyisiä arvioita suurempia. Lisäksi ilmastopolitiikka ei voida tarkastella eristyksissä muista politiikkatavoitteista, jotka saattavat olla vastakkaisia ilmastopolitiikan tavoitteiden kanssa.

Tässä väitöskirjassa esitetään tutkimuksia, joissa numeerisen skenaariomallinnuksen keinoin pyritään avustamaan tehokkaiden ilmasto- ja energiapolitiikkojen muodostamista. Tutkimuksen näkökulma ulottuu globaalin lämpenemistavoitteen kustannustehokkuustarkastelusta alueellisesti tasapuoliseen vähennyskustannusten jakautumiseen ja tästä edelleen tarkasteluihin pääoman riittävyydestä ja kuluttajien energiavalinnoista kehittyvissä maissa. Yhteistä väitöskirjassa esitetyille tutkimusartikkeleille on kaksi erityistä kysymystä: kuinka valittuihin tavoitteisiin päästään kustannustehokkaasti, ja kuinka politiikkoja muodostaessa tulisi huomioida kustannusten kohdentuminen eri ajanhetkillä ja eri toimijoille.

Toisaalta tulokset antavat viitteitä sille, kuinka eri kasvihuonekaasuja tulisi hinnoitella ja kuinka kansainvälinen päästökauppa voisi tukea kustannustehokkaiden päästövähennyskeinojen valintaa ja kustannusten tasapuolista jakautumista. Väitöskirjassa havainnollistetaan myös mahdollisia esteitä tehokkaiden ja tasapuolisten lopputulosten saavuttamiselle. Molemmissa tapauksissa taustalla on kuitenkin sama pyrkimys: tarkastella ja kvantifioida eri politiikkavaihtoehtojen vaikutuksia ja parantaa edellytyksiä perusteltujen politiikkojen ja strategioiden muodostamiselle.

Avainsanat climate policy, energy policy, energy economics, scenario

Preface

It has been a long journey towards finishing this Dissertation, but I hope this has been merely a start for an even longer journey. Done over several years in a number of projects and with different colleagues, the research resembles more a patchwork than a single, thought-out study. The process has been a combination of chance opportunities, deliberate effort, support from others, and determined work towards creating something new that could provide a small bit of help for the humanity to tackle the climate and energy challenges.

During the past seven years I have had the possibility to work with and learn from a large number of great people, and I wish now to express my gratitude for this. Most grateful I am to Ilkka Savolainen and the Climate Change research team at VTT. The exchange of ideas and knowledge within this group has been an important driving force and an enabling factor for this Dissertation. From this great team, I want to thank particularly Sanna Syri and Sampo Soimakallio, who once provided so much guidance and encouragement for a young researcher.

I have had two opportunities to collaborate with the fine researchers from the Energy program of IIASA. These collaborations have given me invaluable experience and introduced me to new research topics. I wish to extend my warmest thanks to the whole research group, and particularly Keywan Riahi and Volker Krey for sharing their tremendous insight. I also thank Sanna Syri and Tiina Koljonen for providing me the opportunity from VTT's side for this collaboration.

I am also grateful to Ahti Salo for his guidance and support in writing the papers and the Dissertation. Particularly his exceptional precision with words has taught me how to convey the insights from research in crisp and clear language. Every co-author deserves a thank you; I hope we can continue the collaboration in the future. I also wish to thank Bas van Ruijven and Mark Howells for devoting their time to the pre-examination of this Dissertation.

We should never work for work alone, but for the people around us. Therefore I wish to thank all the friends I have met, and with whom I have had such good time. And, of course, very special thanks go to my families, mom, dad and Janetta, and Heidi, Eino and Alina, for all the support and good moments during the journey. You – my friends and family – are the ones that make life worth all the effort.

Espoo, 28th of June, 2013
Tommi Ekholm

Academic dissertation

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List of publications

This thesis is based on the following original articles which are referred to in the text as I–V. The articles are reproduced with kind permission from the publishers.

I **Tommi Ekholm**, 2013. Hedging the climate sensitivity risks of a temperature target. Submitted, 21 p.

II **Tommi Ekholm**, Tomi J. Lindroos and Ilkka Savolainen, 2013. Robustness of climate metrics under climate policy ambiguity. Environmental Science & Policy 31, pp. 44–52.

III **Tommi Ekholm**, Sampo Soimakallio, Sara Moltmann, Niklas Höhne, Sanna Syri and Ilkka Savolainen, 2010. Effort sharing in ambitious, global climate change mitigation scenarios. Energy Policy 38, pp. 1797–1810.

IV **Tommi Ekholm**, Hamed Ghoddusi, Volker Krey and Keywan Riahi, 2013. The effect of Financial Constraints on Energy-Climate Scenarios. Energy Policy 59, pp. 562–572.

V **Tommi Ekholm**, Volker Krey, Shonali Pachauri and Keywan Riahi, 2010. Determinants of household energy consumption in India, Energy Policy 38, pp. 5696–5707.

Author’s contributions

In Article [I], Ekholm is the sole author of the paper. Ekholm developed the concept and the calculation model, performed the analysis and wrote the paper.

In Article [II], the concept for the analysis was planned by all authors. Ekholm developed the calculation model, carried out the analysis and wrote the paper. Lindroos and Savolainen commented on the paper.

In Article [III], the concept was planned by Soimakallio, Höhne and Ekholm. Moltmann carried out the Triptych and Multistage calculations. Ekholm performed the scenario calculations, analysed the results, and wrote the paper. Soimakallio, Moltmann, Höhne, Syri and Savolainen provided comments on the paper.

In Article [IV], the concept for the analysis was planned by all authors. The analysis for the capital cost curve assumptions was carried out by Ghoddusi. Scenario model development and analysis was carried out by Ekholm. The paper was jointly written by Ekholm and Ghoddusi, while Krey and Riahi provided comments on the paper.

In Article [V], the concept for the analysis was planned by all authors. Statistical analysis of NSSO data was carried out by Pachauri. Scenario model development and analysis was carried out by Ekholm. The paper was written by Ekholm, while Krey, Pachauri and Riahi provided comments on the paper.

Contents

Articles I–V

1. Introduction

Many activities in the economy, most notably the use of fossil fuels, emit greenhouse gases into the atmosphere. The gases have differing lifetimes and warm the atmosphere at varying rates. The rapid and continuing increase in emissions during the last decades has increased the gas concentrations in the atmosphere considerably since the pre-industrial period. Further down the causal chain, the elevated concentrations increase radiative forcing, defined as the additional warming that solar radiation inflicts on the Earth; and by doing so they slowly increase the temperature in the atmosphere and oceans.

Rising temperature itself is yet not a reason for concern, but rather the associated harmful climatic phenomena that incur damage on ecosystems and human society. Although also some positive effects – such as increased crop yields – have been identified, these are likely to be outweighed by negative effects, including disintegration of major ice sheets, loss of biodiversity, melting of glaciers and increase in extreme weather events. Estimating the magnitude of damages and their dependence on temperature is exceedingly difficult, but it is widely believed that warming exceeding 2°C from the pre-industrial period will exacerbate most of the key impacts (Schneider et al. 2007).

Uncertainty on future development grows along this causal chain, from projected future emissions to possible societal and ecological damages. There is nonetheless a solid outlook that the root of this chain, greenhouse gas emissions, will continue to increase in the coming decades if a business-as-usual pathway will be followed. To prevent this and mitigate climate change, a global climate policy has to be established to control emissions. The emission sources are dispersed throughout the global economy. None of the economic actors that emit greenhouse gases – individuals and companies – has a strong incentive to reduce their own emissions. The reductions require always some economic effort, because activities and production technologies with low or zero emissions are, in some sense, costlier than their conventional emitting counterparts. A requirement for effective policy would thus be to generate incentives for emission reductions by the actors.

Currently, the global climate policy is centred around the negotiations in the United Nations Framework Convention on Climate Change (UNFCCC). Although 195 countries are signatory parties to the convention, only few are committed to binding emission reductions. The Kyoto Protocol of UNFCCC mandated quantitative emission targets for developed countries – except for the US – for the period of 2008 to 2012. Although main emitting countries have also given pledges of emission reductions up to 2020 with varying levels of ambition, no binding agreement has yet been reached for 2020 or beyond.

Part of the difficulty in establishing an extensive climate agreement stems from the intricacy of the problem setting. Indeed, this problem lies in the intersection of two complex systems: climate and society. A large number of actors are involved, and dealing with the climate problem requires decisions and analysis on multiple levels, ranging from global to individual. As the time frame of climate change and its mitigation efforts rang from decades to centuries, a very long time frame needs to be considered when formulating policies. In this setting, the quantification of possible mitigation options and their impacts can help decision makers in developing more informed strategies and policies.

Many unresolved questions remain in the formulation of efficient climate policy. How vigorously should emissions be reduced now and in the far future? How should different greenhouse gases be compared to each other? How can the reductions be realized in an efficient manner; what will they cost; and who can and should pay for them? As climate policy overlaps with energy policy, separate objectives relating to energy issues have to be taken into consideration.

This Dissertation contains five Articles that address questions related to the formulation of efficient climate and energy policy. Approach in all Articles is numerical scenario analysis, with a focus on some aspects of economic efficiency. The larger problem setting examined from two directions: first from the perspective of global efficiency in Articles [I–III], and then from the viewpoint of heterogeneity in the regional and microeconomic levels in Articles [III–V].

Article [I] presents a cost-efficiency problem of meeting a temperature limit under uncertainty and, specifically, provides both a schematic, analytic solution and numerical scenarios on optimal emission quantities and prices. Article [II] looks at how trade-offs between CO_2 and other greenhouse gases could be quantified, particularly in the problem setting of Article [I]. A number of topics are covered in Article [III], ranging from mitigation technologies, regional equity measured through the distribution of mitigation costs, and the effects from possible market imperfections. Article [IV] analyses how the sufficiency of low-cost capital affects mitigation possibilities and costs in Africa. A developing country perspective is maintained in Article [V], which develops an approach for modelling Indian households and proposes strategies to improve access to clean and efficient modern fuels in the poorest households. After summarizing the main findings of these Articles, Section 4 discusses their shared limitations and identifies directions for future research.

2. Global climatic targets and cost-efficiency

How large an effort should be put into the mitigation of climate change globally? This is a central question of global climate policy from a top-down perspective. The standard economic approach for determining the optimal mitigation strategy is to compare the marginal costs of reducing emissions to the marginal benefits from avoiding additional damages due to climate change. Although such cost-benefit analyses have been carried out – for example in integrated assessment models (IAMs) tracing back to Nordhaus (1991) – the applicability of this approach to the climate problem has drawn also considerable criticism due to difficulties in intergenerational equity, aggregate valuation of costs and benefits, and the uncertainty in damages (Azar & Sterner 1996, Tol 2003, Ackerman et al. 2009).

As an alternative to cost-benefit analysis, the cost-efficient attainment of an externally set climatic target has been proposed (see e.g. Ackerman et al. 2009). The target itself can be a result of a political negotiation process, like the 2°C target in the UNFCCC's Copenhagen Accord. The target setting will nevertheless require an evaluation of benefits at some level, if only in an implicit manner. Therefore, the cost-efficiency problem does not answer where the target arises from; only how the exogenously set target can be achieved with least costs. This approach can be portrayed as a special case of cost-benefit analysis where climate damages jump from zero to infinity as the target is breached, thus avoiding the difficulty of monetizing the diverse damages caused by climate change.

Another question, one that underlies the cost-efficiency problem, is how the cost-efficient emission reductions can be brought about in practice. The reduction of greenhouse gas emissions entails economic costs for various actors in the world economy, and there is no central planner who could choose and put the efficient reduction measures into operation. A necessary condition for cost-efficiency is that throughout the world economy, there exists a uniform incentive for emission reductions. This might be a globally uniform emission tax or a price of emission allowance on a global emission market.

A starting point in this Dissertation is a predetermined temperature target; an intent to reach this target in a cost-efficient manner; and a global cap-and-trade system with an emission market that translates the policy aims into a monetary incentive throughout the global economy. The 2°C target is used as an expositional example, and some variations to the exact formulation of this target are also considered.

In this Section, Article [I] looks at the cost-efficient emission pathways and prices for CO_2 under the 2°C target, both in a deterministic manner and also when climatic uncertainties are considered. Then, Article [II] discusses how the relative prices between CO_2 and other greenhouse gases could be set, and what the possible cost implications are. Last, Article [III] considers the functioning of emission markets with respect to attaining a global emission target efficiently, including also some examples on the consequences of market inefficiencies.

2.1 Temperature targets, efficiency and uncertainty

Let us consider a cost-efficiency problem as an externally given climatic target which is to be achieved with minimal economic costs. A mathematical formulation of this is a minimization problem with a state constraint on temperature, for example. Cost minimization gives optimal temporal paths for global annual emissions and marginal prices of greenhouse gases as a result.

The cost-optimization problem is, however, problematic due to the uncertainty on climate sensitivity parameter. Climate sensitivity expresses how much the temperature would rise in equilibrium if radiative forcing were to increase to a level that corresponds to the doubling of CO_2 concentration from the pre-industrial era. Yet, scientific understanding of atmospheric interactions and feedbacks is still so limited that wide and potentially long-tailed probability distributions have been presented to portray possible values of climate sensitivity (Knutti & Hegerl 2008). What makes this parameter critical for a temperature target is that with a considerable uncertainty on climate sensitivity, it is impossible to define realistic emission pathways that would meet the target with certainty. Due to this difficulty, e.g. Keppo et al. (2007) and den Elzen & van Vuuren (2007) have reported the costs of attaining temperature targets with varying levels of probability, resembling the approach of chance-constrained programming.

A different approach for dealing with this uncertainty is taken in Article [I]. The whole future emission pathway needs not – and certainly in practice cannot – be defined at one instant. Instead, the setting of emission targets will likely be a sequential decision-making process, in which the prevailing temperature will be continuously observed and revised estimates of climate sensitivity will be taken into account in subsequent decisions. Such an approach has been already used in the general climate policy context (Manne & Richels 1991, Hammitt et al. 1992, Kolstad 1996), and also specifically for temperature targets (Syri et al. 2008, Johansson et al. 2008, Webster et al. 2008).

Article [I] continues this line of research by providing new theoretical and numerical results, as well as a sensitivity analyses for several factors. Specifically, Article [I] first presents a schematic analytical solution, which considers the climate model only implicitly, but still outlines the optimal *shape* of the expected price path that characterizes the solution. As long as the temperature constraint is not binding, the price grows with the inverse of the selected discount factor, multiplied by the ratio of how changes in current and future emissions would violate the temperature limit. If the temperature effect from an emission impulse decays over time, the latter ratio is slightly below one, and the emission price grows approximately according to the discount rate.

While the shape of the price path is an intrinsic feature of the cost-efficiency problem, the level of the path and the emission pathway are determined by the assumed emission reduction cost curves for different points of time in the future. The problem setting implies that the emission pathway is constrained by the temperature target. This is where the uncertainty of climate sensitivity has to be taken into account.

Article [I] assumes a binomial lattice for the information process, with a parameterization based on Webster et al. (2008). Assumptions on future learning are somewhat speculative, and hence the selected approach should be considered illustrative rather than accurate. Still, the lattice approach is an improvement from the single-shot learning approaches (Syri et al. 2008, Johansson et al. 2008, Webster et al. 2008).

The optimal solution to this stochastic cost-minimization problem can be seen as a hedging strategy against the risk in mitigation costs. The numerical results of Article [I] indicate that hedging calls for more ambitious early actions than what the deterministic use of the most likely value for climate sensitivity would suggest. This result is still merely a principle, and practical support for climate policy requires guidance on the actual levels of annual emissions or emission prices, depending on whether quantitative emission limits or emission taxes are used as tools for implementing climate policy. A sensitivity analysis with the numerical model of Article [I], however, yielded somewhat inconclusive results. The optimal emissions levels and prices vary considerably with the chosen discount rate, and the assumptions on the cost curves also affect the optimal emission prices substantially.

2.2 Relative prices of greenhouse gases

The pricing problem in Article [I] deals mainly with the price of CO_2. Yet, many other greenhouse gases are also emitted. Each gas has different lifetime and warming characteristics in the atmosphere, and thus interacts with the temperature target differently. An efficient climate policy requires that appropriate incentives are in place to reduce all greenhouse gases. In an emission market setting, this equates to the pricing of gases, which is usually done in relation to the price of CO_2. Because there is no intrinsic demand for the reduction of greenhouse gases, the prices have to be set externally, preferably in a way that supports the overall goals of global climate policy. Selecting an appropriate approach for the relative pricing of gases is often called the problem of *common climate metrics*.

Article [II] analyses the cost-efficiency implications of different solutions to the metrics question. The topic has been the focus of active discussions both in the academic and policy fields (see e.g. O'Neill 2000, Fuglestvedt et al. 2003, Shine 2009). Of the proposed metrics, two approaches can be differentiated: the physical metrics compare the gases' climatic implications, differing from each other on how the climatic impact should be measured; whereas the economic metrics value the gases based on some economic optimization framework.

The Global Warming Potential with a 100-year timeframe (GWP_{100}) – a physical metric which compares the integrated radiative forcing of gases over 100 years – has been embedded into multiple policy frameworks, such as the Kyoto Protocol of UNFCCC. Alternative metrics measure, for example, temperature changes in the Global Temperature Change Potential (GTP) with a fixed (Shine et al. 2005) or dynamic timeframe (Shine et al. 2007); the climate damages in Global Damage Potential (GDP) (Kandlikar 1995, Kandlikar 1996), and the cost-efficient prices in Global Cost Potential (GCP) (Manne & Richels 2001).

Although each approach has its own merits, only the GCP is consistent with the cost-efficient formulation of climate policy. However, because the GCP is based on the same pricing approach as that in Article [I], it is also subject to the difficulties presented in the sensitivity analysis of Article [I]. Moreover, the GCP metric is dependent on the exact climatic target that is pursued. Echoing the results of Manne & Richels (2001) and Johansson et al. (2008), Article [II] shows that the GCP yields very different relative prices between CH_4 and CO_2 depending on whether rate-of-change constraints for temperature or hedging strategies are included in the target.

The targets of global climate policy are still ambiguous and open to interpretations. As a result, it is not clear on which target formulation the GCP metric should be based. Furthermore, if the cost-efficiency approach is interpreted only as an approximation to the underlying cost-benefit problem, the metric consistent with policy goals would be GDP instead of GCP. Due to this ambiguity, a definite optimal metric may not exist.

As an alternative, Article [II] explores robust metric values for CH_4; that is, externally set price ratios that would perform well with the three formulations of the 2°C target. The result is that the costs would increase only modestly with a wide range of metric values in all target formulations, when compared to the cost-optimal solution of each formulation. The currently used GWP_{100} falls well into this range, and incurs from 2% to 5% higher costs than the optima. Similar results have been presented also by O'Neill (2003) for a 550 ppm concentration target and by Johansson et al. (2006) for the plain 2°C target. The results of Article [II] indicate also generally that from a cost- efficiency perspective it is safer to overestimate rather than underestimate the metric value of CH_4.

Because the exact objectives of climate policy are ambiguous and benefits from using an exact optimum are small, reasons beyond the immediate policy aims could warrant the use of a sub-optimal metric. Deciding on the exact sub-optimal metric can still be difficult. But based on the results of Article [II], the arguments that have been presented against GWP_{100} – that it does not support a cost-efficient policy or the attainment of temperature targets – do not seem fully justifiable.

2.3 The role of emission markets

Articles [I–II] take the perspective of a social planner – a single actor who seeks to minimize the reduction costs. Reduction measures are aggregated into simple cost curves, estimated from past literature. For this approach to be realistic, it is necessary that the emission prices in Articles [I–II] create an incentive to reduce emissions evenly across the whole global economy. That is, the achievement of economic efficiency necessitates a mechanism that equalizes the marginal cost of emitting greenhouse gases across all actors in the global economy, for example through harmonized emission taxes or emission targets with an efficient emission market.

Global climate policy has predominantly taken the approach of quantitative targets for nations' annual emissions. In this context, an approach similar to Article [I] could be used to define global emission targets, while the agreed climate metrics – as discussed in Article [II] – could be used to aggregate the emissions of different gases to CO_2 equivalents. Thirdly, it would be necessary to establish a global exchange for the limited amount of emission allowances in order to translate the emission target into an emission price, thereby incentivising the emission reductions evenly. This is the point of departure for Article [III].

Article [III] presents a scenario study with a bottom-up IAM, modelling the implications of two emission targets under a global emission market until 2050. The literature for climate change mitigation scenarios with different models and focal points is vast. It should be noted that Article [III] outlines merely some possible realizations, or scenarios, particularly as concerns the reduction technology portfolio. As van Vuuren et al. (2009) note, IAM studies usually exhibit a large reduction potential in the energy supply sector, but a large variation is observed in the potentials of other sectors. Hence the mitigation measures reported in Article [III] merely illustrate how emission targets could be met.

The scenarios of Article [III] provide additional insights into the target setting and efficiency discussion. First, the rates of economic and population growth in the future affect considerably the difficulty of attaining the emission targets, as for example Riahi et al. (2007) have presented. This is manifested in the wide range of marginal costs in Article [III], which result from different assumptions about scenario drivers. Hedging against this uncertainty of the baseline scenario assumption is not considered in Article [I], because such hedging would require a more thorough dissection of the connections between the baseline and the reduction cost curves.

Second, Articles [I–II] assume that the global emission market is efficient, and equalizes the marginal reduction costs throughout the global economy. Many scenario studies, e.g. Keppo & Rao (2007), have analysed the delayed participation of some countries in global climate policy. In contrast, Article [III] considers the possibility that the market itself is inefficient, or that actors do not act on the market purely based on their economic interests. The underlying rationale is that the emission reduction potentials assumed in the IAM model are scattered across multiple countries and sectors; and information asymmetry, search frictions, uncertainty and transaction costs might effect a gap in the marginal valuation of allowances between the supply and demand sides. In addition, an actor that owns a substantial amount of allowances initially could have objectives other than economically efficient climate policy, and therefore refrain from profitable transactions in the allowance market. Both cases result in a large loss of economic efficiency in Article [III]. Although such inefficiencies are beyond the scope of Article [I], the possibility of inefficiencies and potential remedies should be borne in mind when developing efficient strategies for climate policy.

3. International equity, regional heterogeneity

While Section 2 has considered quantitative emission targets reached through a limited amount of emission allowances in the market, it did not address the question who owns the allowances initially. Although this question is not necessarily relevant for the efficiency of climate policy, it nevertheless is a question of equity. The allowances are a valuable, artificially created commodity, and their initial allocation will redistribute wealth. Under efficient markets and certain additional conditions, the questions of efficiency and equity can be separated (see e.g. Manne & Stephan 2005). The equity question nevertheless needs to be settled in order for the countries to voluntarily participate in global climate policy.

The notion of equity in climate change mitigation is explicitly mentioned in Article 3.1 of the UNFCCC. The Article states that the “common but differentiated responsibilities and respective capabilities” of the parties to the UNFCCC should be considered when allocating the mitigation efforts to the parties. The underlying rationale for this is that the parties or countries are heterogeneous: they have distinct emission reduction potentials and capacities to act in the future.

Research on effort sharing has strived to answer how the economic burden from emission reductions could be distributed across countries in an equitable manner. In an effort sharing assessment, countries should be differentiated in three respects. First, the potential for emission reductions under a globally cost-efficient climate policy varies by country (see e.g. van Vuuren et al. 2009). Second, the effective cost for the same measures may vary based on the economic conditions in the country, and even between the actors in a country’s economy. Third, the ability to pay for given reduction measures depends on how affluent a country is.

In the setting of a global emission market, the total cost of global climate policy to a country can be adjusted through the initial allocation of annual emission allowances. High reduction costs relative to a country’s economy could be compensated through additional allowances to that country. As the country would carry out cost-efficient reductions regardless of the additional allocation, it could sell the excess allowances and hence its total costs would be reduced. In this way the countries' costs could be, in principle, adjusted so that equitable cost distribution across the countries would follow.

There are, however, several prerequisites for this approach to work. Reliable estimates on how mitigation potentials and costs vary from country to country are required. In addition to this, heterogeneity and equity could be also considered on a sub-country level.

This Section looks at equity and heterogeneity from two perspectives. First, Article [III] looks at regional distribution of mitigation costs under the market setting described in Section 2.3. Then, Articles [IV–V] analyse issues of heterogeneity, specifically pertaining to the difficulties of implementing emission reduction and energy efficiency measures in developing countries.

3.1 Equitable distribution of costs

When deciding on the initial allocation of emission allowances in a cap-and-trade framework, a solution based on optimality is not possible in the same way as in the cost-efficiency problem setting, for example. Instead, the allocation can be based on, or judged by, a number of proposed equity concepts (see e.g. Ringius et al. 1998). Article [III] takes the approach of vertical equity, meaning that the countries with greater ability should take a proportionally higher burden of the mitigation effort. The burden is measured as the regional mitigation cost relative to the region's GDP. In the vertical equity context, the burden should be proportional with the affluence of a region – measured e.g. with GDP per capita. The equity principle does not, however, define the exact *degree* of correspondence between affluence and an equitable burden.

Article [III] assesses the regional cost distribution resulting from four approaches for the initial allocation in eight scenario settings. The approaches include the simple allocation rules of equal per-capita emissions and equal reductions from 1990 levels; and two slightly more complicated approaches: the Triptych approach behind the intra-EU effort sharing of the Kyoto Protocol (Phylipsen et al. 1998), and the Multistage approach in which countries' efforts are staged based on their state of development (den Elzen et al. 2006). Of these, the per-capita, Triptych and Multistage approaches result in varying degrees of vertically equitable costs. A prerequisite for this result is that these approaches involved large allocations to the least developed regions, making the regions net sellers of emission allowances.

The results of Article [III] also highlight several difficulties that are inherent in effort sharing. The scenarios implied that the trade in allowances can be a major factor in the net costs of climate policy for many regions. The future price of allowances in the scenarios is, however, highly dependent on the background scenario assumptions, and the costs of a single region therefore vary considerably by scenario. This creates a fundamental problem. Even though the initial allocation of allowances is used for balancing the regions' mitigation costs, the monetary value of the allowances is not known *ex ante*. The reliability of estimates on regions' future mitigation cost adds to this uncertainty. *Ex post*, when the market price of allowances can be observed, it is not possible to measure the real cost of mitigation measures. Therefore it is neither possible to project ex ante nor to verify ex post whether an effort sharing approach is, in effect, equitable.

Apart from these difficulties in calculating the economic impacts, the effort sharing rules have a trade-off between being transparent and intelligible, and therefore acceptable for the negotiating parties; and being detailed enough to take the countries' heterogeneous situations into account. In addition, a more detailed representation of heterogeneity requires more detailed and uncertain data, and renders the effort sharing rule more sensitive to its parameterization. Of the three vertically equitable effort sharing approaches, Triptych provides the most coherent distribution of regional costs in the assessed scenarios. However, when the sectoral mitigation potentials in the Triptych approach were recalibrated, the initial emission allocations varied by a factor of two for some countries. Since the monetary value of net allowance trade exceeds several percentage points of GDP for some regions in the scenarios, the choice of calculation parameters could therefore have a substantial effect on some countries' economies.

Effort sharing may be necessary for a global cap-and-trade policy. Although uncertainties make it challenging to achieve equitable outcome with formal rules or models, quantitative assessment can illustrate some possible outcomes, their orders of magnitude, and factors that are critical to achieving a given outcome. Effort sharing will ultimately be a result of political negotiations, and research can assist in this process. In order to aid, however, sufficient confidence in the models should be achieved – that the factors relevant to the different parties have been taken appropriately into account. A deeper enquiry into this direction is done in Articles [IV–V].

3.2 Aspects of heterogeneity

Articles [IV–V] extend the standard approach of most bottom-up IAM's, taking up factors that are of particular importance for developing countries. First, Article [IV] considers the scarcity and price of investment capital, and its implications for emission reductions in electricity generation. Then, Article [V] goes further in the microeconomic direction, modelling the energy choices of Indian households, differentiated by their income level and location. Besides portraying the implications from households' heterogeneity in a modelling framework, Article [V] illustrates that there may be other objectives that can be partially conflicting to the aims of climate policy.

A frequent result in mitigation scenarios, e.g. in Article [III], is that emission reductions necessitate a large increase in investments to the energy system. This pertains particularly to electricity generation, in which zero-emission technologies are more capital intensive than fossil technologies. A typical mitigation scenario exhibits a rapidly increasing electricity generation capacity, accompanied by a shift from fossil to renewable technologies in the technology portfolio. Both of these developments increase the monetary amount of electricity investment from their current levels. However, a developing country may not have access to enough low-priced capital to increase its investments sufficiently. A high marginal price of capital, on the other hand, increases the cost of emission reductions.

In order to take this capital scarcity into account, Article [IV] introduces a wide array of capital cost curves into the energy system model of Africa. A background assumption is a climate change mitigation scenario in which the region acts as a price taker on the global emission market. The technology portfolio and emission levels are different for the capital-constrained scenarios and a reference scenario which assumes a flat 5% cost for capital. This result is important for global mitigation scenarios and effort sharing, which is the topic of Article [III]. It also affects indirectly the costs of global mitigation strategies in Article [I]. Regarding the former, the results of Article [IV] suggest that many mitigation scenarios may have overestimated the developing countries' reductions resulting from a given global emission price level or, conversely, underestimated the price required to meet a given emission level.

The overall contribution of Article [IV] to the discussion on equity and heterogeneity is that differences in the cost of capital affect the countries' costs and possibilities to carry out emission reduction measures. Similar disparities may also be observed inside a single country, because the actors in a country's economy are dissimilar. Factors governing the actors' decisions vary. Aggregating a group of heterogeneous actors into a single representative actor will obscure how individual actors react, and what kind of outcomes a given policy can lead to. The ability to estimate distributional impacts of a policy in a detailed manner is nevertheless important, if equitable outcomes are to be achieved with climate policy.

A more microeconomically detailed modelling approach is introduced in Article [V], which considers the determinants in the energy decision of heterogeneous households in India. The households are divided into ten consumer groups based on their income level and location, differentiated between rural or urban environments. By estimating discount rates and preferences for using different fuels, separately for each of these ten groups, it is possible to reproduce the wide spectrum of actual cooking fuel choices in India with a scenario model similar to those used in Articles [III–IV]. The decision framework indicates that the low inconvenience cost for fuelwood use and the high cost of capital inhibit the low-income households' investments in more efficient cooking appliances. The model enables to estimate separately for each consumer group the possibilities of switching from the inefficient, traditional fuelwood use to modern cooking fuels.

Although the investment decisions in Article [V] are important for improving energy efficiency, the promotion of fossil fuel use seems to conflict with the aims of climate policy. On one hand, a switch to modern cooking fuels will reduce fuelwood use, and probably reduce deforestation emissions resulting from fuelwood collection in some locations. Yet more than this, the positive societal, economic and health implications should be seen as the true merits behind the promoting of modern cooking fuels. As an implication to global climate policy, developing countries are likely to focus on objectives that are not aligned with climate policy. This misalignment will decrease their willingness and ability to reduce greenhouse gas emissions (see e.g. van Ruijven et al. 2011 and Daioglou et al. 2012 for additional discussion).

Against this backdrop, Articles [IV–V] illustrate how the scarcity of capital, non-monetary preferences and intents external to climate policy affect the ability of countries to reduce their emissions, and perhaps often negatively. Although these factors provide a major challenge for a bottom-up approach on effort sharing, both Articles also discuss how effort sharing and global allowance trading could alleviate these difficulties. The emission trading in the scenarios of Article [III] involved large monetary flows to developing countries. How this money would distribute in a developing country’s economy is an open question, and depends on who in that country would own and sell the allowances. Nevertheless, it could provide a partial solution to the capital scarcity problem discussed in Articles [IV–V].

4. Discussion and conclusions

The five Articles in this Dissertation use mathematical modelling to aid in the development of efficient climate and energy policies. They cover multiple perspectives and levels of detail, ranging from the global combat against climate change to the households' energy decisions in developing countries. An overreaching theme is the cost-efficient mitigation of climate change, while Articles [III–V] also discuss related topics that need to be addressed jointly with the efficiency issue.

The Articles advance the knowledge on the cost-efficiency and robustness of emission pathways and prices; the importance of an efficient emission market; considerations on regional equity towards the mitigation costs; and the role of capital price and preferences on mitigation possibilities and energy investment decisions. Moreover, the Dissertation also presents reflective critique and outlines difficulties in the modelling of each problem setting. Both the wide coverage of topics and the motive for the critique pertain to the same source: the focus of modelling has been on the intersection of two complex systems: climate and society.

Several fundamental difficulties can be identified. First, the societal system is populated by individuals and organizations that pursue different objectives. This heterogeneity is one of the focal points in Articles [III–V]. These Articles nevertheless only touch some aspects of heterogeneity relevant to the formulation of climate and energy policies.

Second, all of the Articles share a common problematic detail: discounting. On a microeconomic level, discounting can provide a descriptive view on how cost-of-capital and impatience affect investment decisions, as exemplified in Articles [IV–V]. But even these Articles rely on crude assumptions on appropriate discount rates and used exclusively exponential discounting, although this standard approach might not entail descriptive realism (Frederick et al. 2002). On a macroeconomic level, the applicability of discounting to the climate issue has been the focus of an active debate. Viewpoints have been presented on topics such as how discounting relates to intergenerational equity (Arrow et al. 1996); whether a welfare-substitute for climate damages exists (Neumayer 1999); and what the appropriate discount rate is (see Weitzman 2001 for a survey).

Third, the numerical modelling or optimization approach is usually centred on a single, well-defined problem definition, of which the cost-minimization of Article [I] is an example. Yet, real life problems are seldom this clearly defined. A decision maker who would be in charge of the problem setting in Article [I] does not actually exist. The exact aims of global climate policy are still ambiguous, as is noted in Article [II]. The scope of Article [III] involves multiple decision makers – the negotiating countries – who would all have to accept a solution as an equitable one. Promoting the use of modern fuels in developing countries, as studied in Article [V], is likely to increase emissions and is therefore misaligned to climate change mitigation targets.

These difficulties are not insurmountable. The models will be improved over time, exploring the different facets of climate and energy policy; perhaps first in isolated modelling settings and later in an integrated fashion. Decision makers who are guided by the results need to be aware of the scopes and limitations of quantitative models, and make their decisions recognizing the caveats. A poorly formed model or problem setting may not win the decision makers' confidence.

How could confidence be improved? One approach would be to consider the main uncertainties endogenously inside the modelling setup. This is the approach in Article [I] with regard to climate sensitivity. Although this is not a new concept even in climate policy modelling (Manne & Richels 1991, Hammitt et al. 1992), it could be more widely applied in future research. Other approaches include the consideration of several scenarios as in Articles [III–IV] or several objectives as in Article [II]. A common factor shared by these approaches is that they provide guidance for developing policies that are more resilient to uncertainty.

This is, however, possible only for uncertainties that we are aware of and can quantify. Therefore it is also important to identify new factors that we are currently unaware of or often neglect. As an example, Articles [IV–V] analyse factors that are not truly novel, but mostly disregarded in past IAM's. One future direction would be to identify possible neglected factors, analyse their relevance and later integrate them into the mainstream of IAM's.

Through continued research and learning, the uncertainties on climate dynamics can be expected to diminish over time. Meanwhile, present-day decisions have to be based on currently available knowledge. As new approaches and models are developed, consideration should be also given to how different actors take decisions. It is not the models, but the decisions that drive development in the fields of climate and energy policy, and therefore understanding how these decisions are made is vital. Quantitative, integrated analysis of these issues has merely the role of providing informed guidance on possible options, outcomes and risks associated with the decisions.

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References

Ackerman, F., DeCanio, S.J., Howarth, R.B. & Sheeran, K. 2009, "Limitations of integrated assessment models of climate change", *Climatic Change,* vol. 95, no. 3-4, pp. 297-315.

Arrow, K.J., Cline, W.R., Maler, K.-., Munasinghe, M., Stiglitz, J.E. & Squitieri, R. 1996, "Intertemporal Equity and Discounting" in *Climate Change 1995: Economic and Social Dimensions*, eds. J.P. Bruce, H. Lee & E. Haites, Cambridge University Press, Cambridge, England, pp. 125-144.

Azar, C. & Sterner, T. 1996, "Discounting and distributional considerations in the context of global warming", *Ecological Economics,* vol. 19, no. 2, pp. 169.

Daioglou, V., van Ruijven, B.J. & van Vuuren, D.P. 2012, "Model projections for household energy use in developing countries", *Energy,* vol. 37, no. 1, pp. 601-615.

den Elzen, M.G.J., Berk, M., Lucas, P., Criqui, P. & Kitous, A. 2006, "Multi-stage: A rule-based evolution of future commitments under the climate change convention", *International Environmental Agreements: Politics, Law and Economics,* vol. 6, no. 1, pp. 1-28.

den Elzen, M.G.J. & Van Vuuren, D.P. 2007, "Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs", *Proceedings of the National Academy of Sciences of the United States of America,* vol. 104, no. 46, pp. 17931-17936.

Frederick, S., Loewenstein, G. & O'Donoghue, T. 2002, "Time Discounting and Time Preference: A Critical Review", *Journal of Economic Literature,* vol. 40, no. 2, pp. 351-401.

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P. & Skodvin, T. 2003, "Metrics of climate change: Assessing radiative forcing and emission indices", *Climatic Change,* vol. 58, no. 3, pp. 267-331.

Hammitt, J.K., Lempert, R.J. & Schlesinger, M.E. 1992, "A sequential-decision strategy for abating climate change", *Nature,* vol. 357, no. 6376, pp. 315-318.

Johansson, D.J.A., Persson, U.M. & Azar, C. 2008, "Uncertainty and learning: Implications for the trade-off between short-lived and long-lived greenhouse gases", *Climatic Change,* vol. 88, no. 3-4, pp. 293-308.

Johansson, D.J.A., Persson, U.M. & Azar, C. 2006, "The cost of using global warming potentials: Analysing the trade off between CO2, CH4 and N2O", *Climatic Change,* vol. 77, no. 3-4, pp. 291-309.

Kandlikar, M. 1996, "Indices for comparing greenhouse gas emissions: Integrating science and economics", *Energy Economics,* vol. 18, no. 4, pp. 265-281.

Kandlikar, M. 1995, "The relative role of trace gas emissions in greenhouse abatement policies", *Energy Policy,* vol. 23, no. 10, pp. 879-883.

Keppo, I., O'Neill, B.C. & Riahi, K. 2007, "Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios", *Technological Forecasting and Social Change,* vol. 74, no. 7, pp. 936-961.

Keppo, I. & Rao, S. 2007, "International climate regimes: Effects of delayed participation", *Technological Forecasting and Social Change,* vol. 74, no. 7, pp. 962-979.

Knutti, R. & Hegerl, G.C. 2008, "The equilibrium sensitivity of the Earth's temperature to radiation changes", *Nature Geoscience,* vol. 1, no. 11, pp. 735-743.

Kolstad, C.D. 1996, "Learning and stock effects in environmental regulation: The case of greenhouse gas emissions", *Journal of Environmental Economics and Management,* vol. 31, no. 1, pp. 1-18.

Manne, A.S. & Richels, R.G. 2001, "An alternative approach to establishing trade-offs among greenhouse gases", *Nature,* vol. 410, no. 6829, pp. 675-677.

Manne, A.S. & Richels, R.G. 1991, "Buying greenhouse insurance", *Energy Policy,* vol. 19, no. 6, pp. 543-552.

Manne, A.S. & Stephan, G. 2005, "Global climate change and the equity-efficiency puzzle", *Energy,* vol. 30, no. 14, pp. 2525-2536.

Neumayer, E. 1999, "Global warming: discounting is not the issue, but substitutability is", *Energy Policy,* vol. 27, no. 1, pp. 33-43.

Nordhaus, W.D. 1991, "To Slow or Not to Slow: The Economics of The Greenhouse Effect", *The Economic Journal,* vol. 101, no. 407, pp. pp. 920-937.

O'Neill, B.C. 2003, "Economics, natural science, and the costs of global warming potentials. An editorial comment", *Climatic Change,* vol. 58, no. 3, pp. 251-260.

O'Neill, B.C. 2000, "The jury is still out on Global Warming Potentials", *Climatic Change,* vol. 44, no. 4, pp. 427-443.

Phylipsen, G.J.M., Bode, J.W., Blok, K., Merkus, H. & Metz, B. 1998, "A Triptych sectoral approach to burden differentiation; GHG emissions in the European bubble", *Energy Policy,* vol. 26, no. 12, pp. 929-943.

Riahi, K., Grübler, A. & Nakicenovic, N. 2007, "Scenarios of long-term socio-economic and environmental development under climate stabilization", *Technological Forecasting and Social Change,* vol. 74, no. 7, pp. 887-935.

Ringius, L., Torvanger, A. & Holtsmark, B. 1998, "Can multi-criteria rules fairly distribute climate burdens? OECD results from three burden sharing rules", *Energy Policy,* vol. 26, no. 10, pp. 777-793.

Schneider, S.H., Semenov, S., Patwardhan, A., Burton, I., Magadza, C.H.D., Oppenheimer, M., Pittock, A.B., Rahman, A., Smith, J.B., Suarez, A. & Yamin, F. 2007, "Assessing key vulnerabilities and the risk from climate change" in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental*

Panel on Climate Change, eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson, Cambridge University Press, Cambridge, UK, pp. 779-810.

Shine, K.P. 2009, "The global warming potential-the need for an interdisciplinary retrial", *Climatic Change,* vol. 96, no. 4, pp. 467-472.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B. & Stuber, N. 2007, "Comparing the climate effect of emissions of short- and long-lived climate agents", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 365, no. 1856, pp. 1903-1914.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K. & Stuber, N. 2005, "Alternatives to the Global Warming Potential for comparing climate impacts of emissions of greenhouse gases", *Climatic Change,* vol. 68, no. 3, pp. 281-302.

Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H. & Peltola, E. 2008, "Global energy and emissions scenarios for effective climate change mitigation-Deterministic and stochastic scenarios with the TIAM model", *International Journal of Greenhouse Gas Control,* vol. 2, no. 2, pp. 274-285.

Tol, R.S.J. 2003, "Is the uncertainty about climate change too large for expected cost-benefit analysis?", *Climatic Change,* vol. 56, no. 3, pp. 265-289.

van Ruijven, B.J., van Vuuren, D.P., de Vries, B.J.M., Isaac, M., van der Sluijs, J.P., Lucas, P.L. & Balachandra, P. 2011, "Model projections for household energy use in India", *Energy Policy,* vol. 39, no. 12, pp. 7747- 7761.

van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E. & Kram, T. 2009, "Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials", *Energy Policy,* vol. 37, no. 12, pp. 5125-5139.

Webster, M., Jakobovits, L. & Norton, J. 2008, "Learning about climate change and implications for near-term policy", *Climatic Change,* vol. 89, no. 1-2, pp. 67-85.

Weitzman, M.L. 2001, "Gamma Discounting", *The American Economic Review,* vol. 91, no. 1, pp. 260-271.

ARTICLE I

Hedging the climate sensitivity risks of a temperature target

Submitted manuscript.

Hedging the climate sensitivity risks of a temperature target

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Abstract

This paper addresses the problem of meeting a predetermined temperature target cost-effectively under uncertainty and gradual learning on climate sensitivity. An analytical solution to a stochastic cost-minimization problem with a temperature constraint is first provided, portraying an outline of the risk hedging solution. Then, numerical stochastic scenarios with cost curves fitted to recent climate change mitigation scenarios are presented, illustrating both the range of possible future pathways and the effect of uncertainty to the solution. Last, the effect of several different sets of assumptions on the optimal hedging strategy are analyzed. The results highlight that the hedging of climate sensitivity risk calls for deeper early reductions, although the possibility of different assumptions prevents providing accurate policy guidance.

Keywords: climate change mitigation, climate sensitivity, uncertainty

1. Introduction

The vigour with which climate change should be mitigated has been debated for long. To address the question, the economic approach of weighing costs of reducing emissions against the benefits from climate change mitigation has been used extensively, e.g. with integrated assessment models tracing back to Nordhaus (1991). This approach has, however, drawn criticism for incorporating judgements on intertemporal and interregional equity

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(e.g. Azar and Sterner, 1996), because costs and benefits in different points of time and location have to be aggregated into a single value.

Another source of difficulties are the uncertainties involved. Both the damages from climate change and costs from its mitigation span several decades or centuries. The warming induced by a given concentration of greenhouse gases is still uncertain, and the damages to society from a given temperature increase are even less known. Assuming a *prior* probability distribution for the damages and adopting sequential decision making strategy under learning, this uncertainty may in principle be hedged (Manne and Richels, 1991; Hammitt et al., 1992; Kolstad, 1996). With a fat-tailed probability distribution for climate damages, however, low-probability catastrophic events dominate the cost-benefit analysis (Weitzman, 2009; Ackerman et al., 2010), making the prior distribution a critical assumption in the analysis. Moreover, sufficiently large uncertainty might even prevent using the cost-benefit comparison altogether (Tol, 2003).

Such concerns have prompted e.g. Ackerman et al. (2009) to suggest temperature targets which would be set outside of any model-based balancing of expected costs and benefits, and which would be pursued with a least cost strategy. This is also what has happened on the climate policy arena, with the 2°C target written e.g. into the Copenhagen Accord of the UNFCCC.

A cost-effective solution to a predetermined temperature target is the point of departure for this paper. The temperature target, nevertheless, has to arise from somewhere. Should the target be a result of rational decision making, some kind of cost-benefit analysis – if only implicit – needs to take place. This paper does not consider the process that leads to the temperature target, but takes it as given. As such, this paper can be seen to address solely the cost side of the cost-benefit equation.

Although a temperature target avoids the uncertainty of valuing climate damages, substantial uncertainty is still involved in climate sensitivity, i.e. the equilibrium temperature increase from a doubling of CO_2 concentration in the atmosphere. Settling this uncertainty is likely to be easier than that of climate damages, for as a scientific parameter it is not a question of value judgements, and might be gradually resolved over time. This learning also gives rise to sequential decision making. The emission reductions that are required to meet the temperature target become gradually more certain, and optimal emission pathways will be revised to reflect this new information on climate sensitivity.

Meeting a temperature target with minimal mitigation costs under uncertainty on climate sensitivity is not a completely new research topic. Earlier work by e.g. Syri et al. (2008) and Webster et al. (2008) have analyzed hedging strategies against the uncertainty, while assuming a one-shot learning in or around 2040. Johansson et al. (2008), on the other hand, employed a slightly more complex framework of sequential learning for valuing CH_4 against the value of CO_2.

This paper extends this line of research by improving the formalism of meeting a predetermined temperature target cost-effectively under uncertainty, and provide numerical stochastic scenarios on reaching the 2°C target. First, section 2 provides an analytical solution to a schematic, recursive cost minimization problem under a temperature limit. Although the theory section gives insight into what the solution of the problem will look like, the section may be skipped without a large hindrance to grasp the insights from the rest of the paper. Second, a simplified numerical optimization model for emission reductions and associated costs is presented. The model incorporates estimates on global reduction costs and sequential learning on climate sensitivity, and produces stochastic scenarios for emission levels and prices. Several different assumption sets are analyzed in order to identify factors that affect the solution the most. Finally, a concluding section discusses implications of the results and potential directions for further work.

2. An analytical consideration

Let us start with a theoretical model for minimizing the emission abatement costs under a given temperature target. The same problem setting is elaborated further and more explicitly in the numerical analysis in sections 3 and 4. Elements to be captured by the model include possible future emission levels, the cost associated with reaching these levels, climate dynamics for translating the emission pathway to changes in global mean temperature, and uncertainties associated with the climate dynamics. Some simplifications have to be made, but only to an extent that robust implications can still be drawn from the model.

The model assumes a baseline of greenhouse gas emissions that would take place if no measures for emission control are taken. Control measures incur expenses, represented by a time-dependent cost function that is increasing with higher reduction levels. The decision maker chooses sequentially the level of emission reductions for the current time period, while minimizing the expected long-term costs from reductions that are necessary to meet the emission target. For simplicity, no path-dependency is assumed for the baseline or costs, i.e. that past emission reductions do not affect the emission baseline or the reduction cost curves in the future.

For climate dynamics, the analytical model takes a schematic approach without explicitly specifying the equations for the climatic system. The level of climate sensitivity is uncertain, and this uncertainty decreases gradually through learning. The learning process is modelled as a scenario tree (see e.g. Ruszczynski and Shapiro, 2003, section 3.2), where each single scenario represents one possible learning path and final realization of the climate sensitivity parameter. The initial state reflects the current probability distribution for climate sensitivity, and future states gradually converge into some realization from this prior distribution.

The temperature constraint has to be met at all future periods and possible realizations of climate sensitivity. This is a bold requirement, and can generally render the problem infeasible if the constraint is close to binding and there is limited possibility to reduce emissions, or if the temperature change in the next period can be arbitrarily large. Here we assume that the problem does have a solution. In the numerical scenarios of sections 3 and 4 the existence of solution is ensured with two assumptions: that the highest possible realization of climate sensitivity is finite, and that the uncertainty will be resolved by 2080, which is before the considered temperature constraint typically becomes binding.

The cost minimization problem at time t is defined as

$$\min_r \left\{ E_t \left[\sum_{\tau=t}^{\infty} \beta^\tau c_\tau(r_{\tau,s}) \right] \; \middle| \; \begin{array}{l} T(x_{\tau,s}) \geq 0,\ x_{\tau+1,s} = f_s(x_{\tau,s}, r_{\tau,s}),\ \forall s, \tau \geq t, \\ r_{\tau,s_1} = r_{\tau,s_2} \quad \text{if } S(\tau,s_1) = S(\tau,s_2) \end{array} \right\}, \tag{1}$$

where

- $E_t[\cdot]$ indicates expectations with the information at the time t.
- β is the discounting factor,
- s indicates the learning scenario for climate sensitivity,
- $r_{\tau,s}$ indicates the amount of emission reductions,

- $c_\tau(r_{\tau,s})$ is the cost corresponding to the reduction $r_{\tau,s}$,
- $x_{\tau,s}$ is a general climatic state variable, including the level of temperature,
- $T(x_{\tau,s})$ is the difference between the maximum allowed and current temperature (i.e. slack to the temperature target),
- $f_s(x_{\tau,s}, r_{\tau,s})$ is the transfer equation for the climatic state variable, corresponding to the climate sensitivity in scenario s
- $S(\tau, s)$ indicates the node in the scenario tree corresponding to scenario s at time τ,

The state of the world $x_{t,s}$ includes in a general manner all relevant variables, such as temperature and atmospheric concentrations of greenhouse gases. Future evolves according to the transfer function f_s – which includes e.g. the climate dynamics – and depends on the emission reductions r. The temperature target is represented with $T(x_{t,s})$ as the difference between the target and current temperature, and is required to be positive. The scenario tree is represented with a mapping $S(\tau, s)$, which connects an information state (τ, s) to a node in the scenario tree. All states (τ, s) that are in the same node have the same history of past decision variables and learning, and therefore are required to result in the same decision variable at time τ.

The problem setting is defined for the state of knowledge at time t. As time evolves, the temperature change will be observed and the uncertainty in climate sensitivity will be reduced. With this new information in the future, the plan for current and future reductions r may be changed. This creates a recursive structure for the problem. As we solve the problem at time t, we face a similar problem at time $t+1$, but with the baseline emissions and marginal costs shifted by one period, a new climatic state $x_{t+1,s}$ and new information on climate sensitivity, reflected through the expectation $E_{t+1}[\cdot]$. Due to this, the future mitigation costs need to be considered through expectations, as the anticipated future emission reductions might be readjusted later.

The problem in (1) can be solved by first including the temperature constraints in a Lagrangian function, and writing the problem as a recursive minimization problem. For this, the reduction costs are first re-written as

$$\tilde{c}(x_{\tau,s}, x_{\tau+1,s}) = \{c(r_{\tau,s}) | x_{\tau+1,s} = E_t\left[f_s(x_{\tau,s}, r_{\tau,s})\right]\}, \qquad (2)$$

i.e. as the cost for bringing the system from state $x_{\tau,s}$ to an expected state $x_{\tau+1,s}$. Then, the temperature constraints can be included in the minimization through the Lagrangian multipliers $\lambda_{\tau,s}$. Note that the probabilities with which each future temperature constraint will be materialized – due to being associated with the climate sensitivity state that will unltimately be realized – are reflected in the Lagrangian multipliers for future periods. Alternatively, we can divide the future Lagrangian multipliers with the associated probabilities and then take these multipliers inside the expectation. The Lagrangian function $\mathscr{L}$ can be then written in a recursive form

$$\mathscr{L}_t(x,\lambda) = \tilde{c}_t(x_t, x_{t+1}) + \lambda_t T(x_t) + \beta E_t\left[\mathscr{L}_{t+1}(x,\lambda)\right], \tag{3}$$

where x indicates the vector of states acting now as decision variables. The scenario indices have been omitted in the recursive formulation to simplify notation.

If we write the optimal value of the minimization problem as a value function $V_t(x_t)$, dependent on the current state x_t, the problem of (1) can be written in a recursive form

$$\begin{aligned} V_t(x_t) = \min\nolimits_{x_{t+1},\lambda_t}\{&\tilde{c}_t(x_t, x_{t+1}) + \lambda_t T(x_t) + \beta E_t\left[V_{t+1}(x_{t+1,s})\right] \\ &\qquad\qquad\qquad\qquad \mid T(x_{t+1,s}) \geq 0\,\forall s,\ \lambda_t \geq 0\}. \end{aligned} \tag{4}$$

This form reflects the recursive nature of the problem. We wish to minimize the sum of costs occurring now and the present value of costs in the next step, while ensuring that the temperature constraint still holds in the next step[1]. Further, the formulation of (4) can be solved through standard methods for recursive problems (e.g. Ljungqvist and Sargent, 2004), i.e. combining the first-order optimality condition and the envelope theorem for (4). This yields

$$\tilde{c}_t^{(2)}(x_t, x_{t+1}) + \beta E_t\left[\tilde{c}_{t+1}^{(1)}(x_{t+1,s}, x_{t+2,s}) + \lambda_{t+1,s} T'(x_{t+1,s})\right] = 0, \tag{5}$$

where $\tilde{c}_t^{(n)}$ denotes the derivative with regard to n^{th} argument of $\tilde{c}_t$.

A more intuitive form for (5) is gained if the marginal costs are written

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[1] The temperature constraints at later timesteps are handled recursively by the problem in the next step, presented by $V_{t+1}(x_{t+1,s})$

again as a function of the reduction level ${r_t}^2$. Then, optimal reductions imply

$$c_t'(r_t(x_t, x_{t+1})) = \beta E_t \left[c_{t+1}'(r_{t+1,s}(x_{t+1,s}, x_{t+2,s})) \frac{r_{t+1,s}^{(1)}(x_{t+1,s}, x_{t+2,s})}{-r_t^{(2)}(x_t, x_{t+1,s})} \right. \qquad (6)$$
$$\left. + \frac{\lambda_{t+1,s} T'(x_{t+1,s})}{-r_t^{(2)}(x_t, x_{t+1,s})} \right].$$

This equation is the solution to the problem, creating a connection between marginal reduction costs – i.e. alternatively the market prices of emissions or the optimal emission tax level – at the current state and expected future state. Note that the optimal emission levels are directly prescribed by the optimal marginal costs.

To build insight to (6), we might first disregard the two ratios on the right side of the equation. Then the expected value of emission price increases according to the discount factor. The first ratio, between marginal reductions now and in the next step, acts as a multiplier for the expected future emission price. This reflects the climate dynamics, measuring how a deviation in current emissions should be compensated later on in order to bring the system on track. Should the temperature depend merely on the cumulative emissions, the ratio would always be one[3]. Alternatively, if we assume a climate response based on additative, decaying emission impulses, the required correcting action done at time $t+1$ is slightly smaller than the deviation at time t, and the ratio should be slightly below one.

Finally, the last term on the right side of the equation (6) brings in the price effect from the temperature constraint at time $t+1$, if the constraint is binding. This increases the emission price at time t. Not much can be said from the magnitude of this effect in a generic sense, though, but should the effect be relatively small, the last term may be seen as to reduce the discounting effect that would otherwise mainly drive the development of the emission price. Therefore, as soon as the temperature target becomes binding, the price ceases to grow exponentially.

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[2] Here, the reductions are written as $r_t(x_t, x_{t+1})$, i.e. as the reductions that are necessary to bring the system from x_t to the state x_{t+1}. Note that $r_t^{(1)} > 0$, and $r_t^{(2)} < 0$, i.e. that a higher current state – e.g. concentration or temperature – requires more reductions, and higher future state requires less reductions.

[3] Note that $r_t^{(2)} < 0$, i.e. $-r_t^{(2)} > 0$

3. A simplified numerical experiment

The analytical solution of equation (6) frames how current actions and future expectations should be balanced to achieve the target cost-effectively. For practical policy guidance, actual numbers are needed. The numerical results are presented in two parts. First, a simplified model is presented in this section. Despite some inaccuracies and loss of realism, the results from this model serve as a connection to the analytical model of section 2 and as a reference point for further analysis. Later in section 4, a number of intricacies and alternate assumptions are taken into account.

3.1. The cost of reducing emissions

As in the analytical treatment, the numerical model assumes a baseline projection for emissions and predetermined cost curves for reducing them. The emission levels for CO_2, CH_4 and N_2O and marginal reduction costs were gathered from existing climate scenario literature (Calvin et al., 2009; Gurney et al., 2009; Krey and Riahi, 2009; Loulou et al., 2009; van Vuuren et al., 2010), spanning five different integrated assessment models, 23 climate change mitigation scenarios and a baseline scenario for each model. Thus, these provide a wide range of different scenario and modelling assumptions, and presumably a representative set for fitting the cost curves for the model. The emission levels, aggregated to CO_2 equivalents with 100 year Global Warming Potentials (GWPs), as the function of marginal abatement costs are presented in Figure 1 for years 2020, 2050 and 2100.

For the baseline emissions, the average of five models was assumed, separately for each decade until 2100. Also for each decade, a such marginal abatement cost curve was fitted which – combined with the baseline assumption – would correspond to the relation between emissions and marginal costs in the scenarios. However, a single marginal cost curve does not capture the range of variability between the different scenarios, as is evident from Figure 1. Instead, two separate curves of the form $r = \alpha c^{\beta}$ were described in a way that they correspond to the higher and lower envelopes of the scenario results[4]. The two envelopes therefore represent the range of correspondences between emission level and marginal costs in the literature.

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[4] A notable feature in the scenarios of Figure 1 is the variance of baseline emissions in 2020. Due to this, it might seem that the fitted curves do not correspond well to the original scenarios. However, what matters for the solution of the cost-minimization

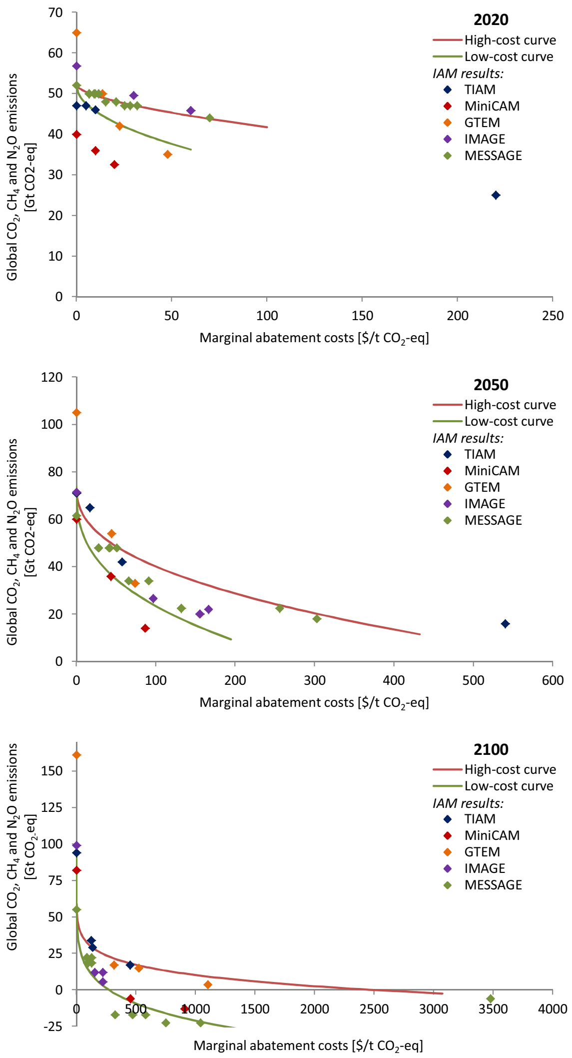

Figure 1: Marginal costs for reaching desired emission levels, based on scenarios from five integrated assessment models (Calvin et al., 2009; Gurney et al., 2009; Krey and Riahi, 2009; Loulou et al., 2009; van Vuuren et al., 2010). Two separate curves corresponding to the high-cost and low-cost envelopes of the scenarios are used in the cost minimization model.

The straightforward use of predetermined marginal cost curves, fitted to the scenario results, might not appear as an entirely sound approach. After all, the emissions and marginal costs are a result of intertemporal optimization and decisions that span several decades. Thus it would not be realistic to move freely from one point to another in the cost curves. Another concern might be that the fitted curves do not correspond to a single scenario, but combine different scenarios on different time periods.

The first issue is alleviated by the fact that an intertemporal optimization also takes place in our cost-minimizing framework, and the optimal emission pathway does not jump arbitrarily from slight to steep emission reductions. Regarding the second concern, the cost curves employed should be taken as expositional, portraying in a general way the range of possible scenarios. What should nevertheless be borne in mind, is that the low-cost and high-cost curves represent scenarios in which the costs remain low or high for the entire time frame. Further work should be done to take the dynamic and uncertain nature of the cost curves into account.

3.2. Climate sensitivity and its uncertainty

The other main component in our cost-minimizing model is the uncertainty in climate sensitivity, and how it might be reduced in the future. Multiple probability distributions have been presented for the current state, but few estimates exist on the future evolution of the uncertainty.

Past scenario work on the hedging of climate sensitivity risks (Syri et al., 2008; Johansson et al., 2008; Webster et al., 2008) have assumed a single-shot learning around and 2040, with Johansson et al. (2008) also exploring a three stepped learning process until 2045. The gradual nature of learning might be extended even further, as new information is obtained decade after decade. Moreover, it seems unlikely that the uncertainty would be resolved during the next decades. For example, Webster et al. (2008) estimated a 20–40% reduction in uncertainty during next 20-50 years using a Bayesian learning model. Over a more longer term, the relative standard deviation would be reduced by some 75% by 2080. If the possibility that the observed increase in temperature is not anthropogenic, the time frame required for full learning could extend dramatically (Leach, 2007).

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problem is with what marginal cost a given emission level may be reached. The level of baseline emissions affects the total costs, but not the optimal emission level or emission pricing.

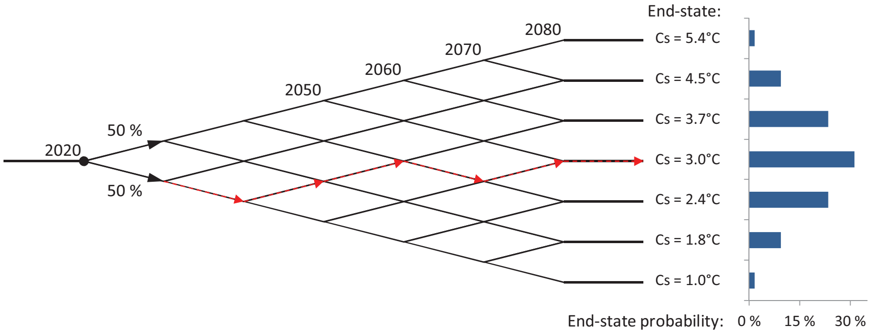

Figure 2: A binomial lattice for the information process on climate sensitivity (Cs). In each node, the highest or lowest possible value of climate sensitivity is ruled out with a probability of 50%. The end-state probabilities are set according to the symmetric probability distribution of Knutti and Hegerl (2008). One possible path through the lattice is illustrated with red arrows.

Therefore, instead of a single, sudden learning event, an information process in the form of a binomial lattice is introduced to the cost-minimization model. In the process, the uncertainty is gradually narrowed down by excluding with a 50% probability either the lowest or highest possible value of the discretized distribution every 10 years. The probabilities of final states were set according to the symmetric distribution of Knutti and Hegerl (2008). Following the results of Webster et al. (2008), the process was parameterized with 7 possible values for climate sensitivity, with the actual realization resolved in 2080. The specified binomial lattice is portrayed in Figure 2.

3.3. A risk-hedging strategy for the 2° C target

We are now ready to portray a strategy for hedging against mitigation cost risks due to uncertain climate sensitivity. As mentioned earlier, a simplified – perhaps overly simplified – case is presented first to highlight the overall nature of the risk hedging strategy. Later, section 4 adds further considerations and provides sensitivity analysis for the hedging strategy.

The cost curves of Figure 1 and the uncertainty-resolution process of Figure 2 were implemented in a stochastic TIMES modelling framework, using the climate module of the ETSAP-TIAM model (see e.g. Loulou and Labriet, 2008; Ekholm et al., 2010). For simplicity, only the low-cost curves of Figure 1 are used in this section, and all gases are converted to CO_2

in the climate module using 100 year GWPs. High-cost curves and specific atmospheric properties of CH_4 and N_2O are taken into account later in section 4. The mitigation costs, the present value of which is being minimized, are discounted with a 5% rate.

As a result, the cost minimization under the 2°C target and uncertainty on climate sensitivity yields stochastic scenarios on the optimal emission levels and prices, presented in Figure 3. The model was run until 2200 by extending baseline emissions and cost curves of 2100 as constant, but results are presented only up to 2100 in order to avoid horizon effects. For comparison, the figure presents also optimal solution of a deterministic case with the climate sensitivity set to 3°C, i.e. the most probable value.

In both cases, the expected value of marginal costs – i.e. optimal emission prices – increase according to equation (6): first approximately by the discount rate and later, as the temperature constraint approaches and eventually becomes binding, at a lower rate. Due to the uncertainty, the expected marginal costs are higher in the stochastic case than in the deterministic one practically throughout the time frame. This is associated with higher emission reductions in the stochastic case during the first half of the century. Later, however, the convergence of marginal cost in the deterministic, and of expected marginal cost in the stochastic case means that the expected emission level is higher in the stochastic case due to the convexity of the cost curve[5]. In practice this means that more ambitious early reductions in the hedging strategy will allow higher expected emissions later in the future.

The wide distribution of prices across individual scenario realizations is also a point of interest. After 2030, each learning event might trigger either a considerable decline in price, or a two- to threefold increase, both with a 50% probability, within the next 10 years. This is already an important risk factor for investments with holding periods of several decades, and might hinder the effectiveness of emission pricing (Fuss et al., 2009).

Some questions also arise from Figure 3. First, are negative emissions by 2070 a sound assumption? As the possibility of such deep reductions directly affects the necessary level of hedging, alternate cost curves should also be considered. Second, are the changes in the emissions too rapid in the

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[5] A convex curve translates a distribution of marginal cost with mean c onto a distribution emissions, the mean of which is higher than the emissions that correspond to a single marginal cost c.

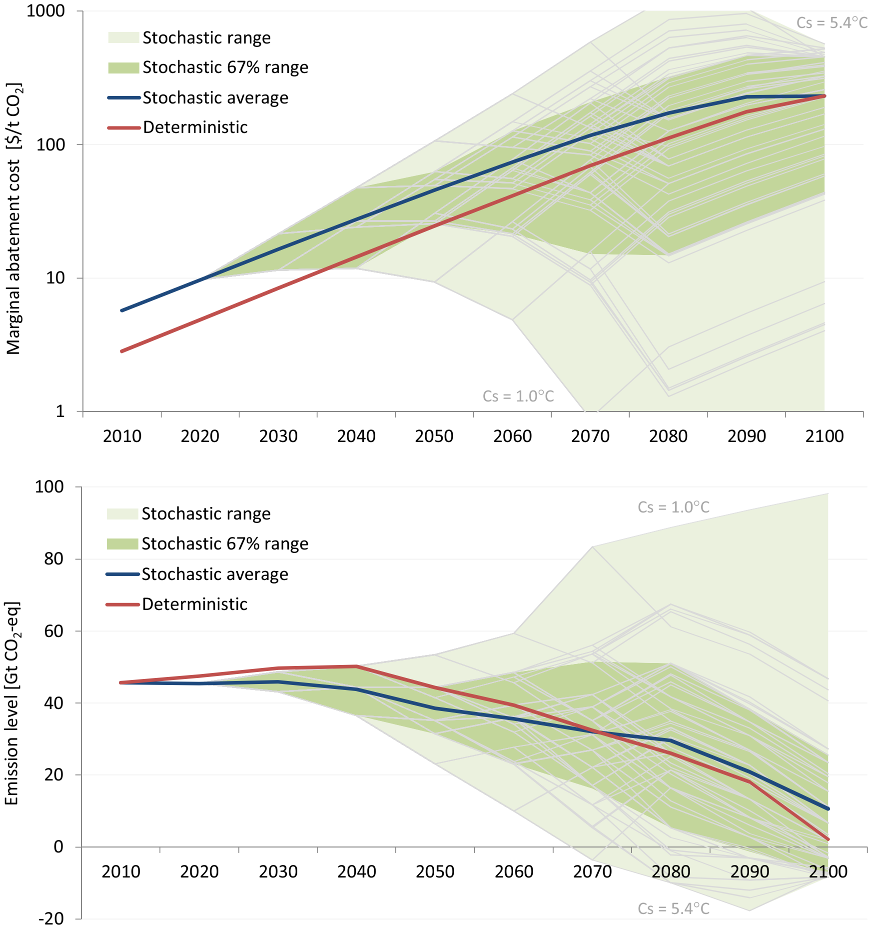

Figure 3: Stochastic pathways for cost-optimal reaching of the 2°C target under uncertainty on climate sensitivity. The top pane presents marginal costs of emissions, i.e. optimal emission prices, and the lower pane shows the level of global greenhouse gas emissions.

individual scenario realizations? In practice there are rigidities due to long capital lifetimes, policy inertia and maximal technology dispatch rates that might constrain the flexibility of readjusting emission levels.

4. Adding realism – a sensitivity analysis

The hedging strategy presented in Figure 3, however illustrative, is rather simplified and does not provide sufficiently exhaustive treatment towards different assumptions.

An important bit of realism is to take the different climatic impacts of CH_4 and N_2O into account. A likely effect from the simplification in section 3 is that the required emission reductions are underestimated, because a conversion of CH_4 into CO_2 with 100 year GWP's leaves some of the warming unaccounted with timeframes shorter than the 100 years. To highlight the effect of this simplification, the results will be later presented with both approaches: with all gases converted to CO_2 equivalents or with separate abatement cost curves and warming impacts being used for CO_2, CH_4 and N_2O.

Two important factors related to the emission reductions are the assumptions on cost curves – particularly the possibility of reaching negative emissions in the distant future – and the flexibility of emission reductions. Towards the first issue, the set of high-cost emission reduction curves from Figure 1 was also introduced to the model. The second warrants some additional discussion.

Although global emission targets could be readjusted every ten years in principle, directing actual emissions to the target might be trickier. Upward inflexibility for adjusting the emission level arises from long capital lifetimes, which is several decades in electricity generation for example. Downward inflexibility might result from the inability to increase the reducing capacity at a sufficient rate, including effects from technological learning. Some additional inertia might also result from a necessary level of commitment to climate policy. As inflexibilities hinder optimal readjustments, they are likely to increase the emission reduction costs.

Here, only the long lifetime of reduction capacity is considered. As an alternative to the flexible approach used section 3, a 20 year capacity lifetime is assumed. That is, the emission reductions initiated at time t define a lower bound for emission reductions at time $t + 1$. If emission reductions at time $t + 1$ are greater than at time t, the difference of these reductions correspond to the emission reduction capacity initiated at time $t+1$, and define the lower bound for time $t+2$. Regarding the case with capital lifetime, it is good to note that the analytical results of section 2 do not hold, because intertemporal dependencies were not considered in the analytical model. Further analysis on the rigidities of emission reduction dynamics might be required in the future.

Last, an important question is what discount rate should be used. This problem is perhaps more simple than in cost-benefit analyses, as we are now considering only technical reduction costs at different points in time. Still, using a single discount rate globally is perhaps a questionable assumption given that there exists notable differences in the marginal productivity of capital between regions. The problem setting at hand merely allows the treatment of this through different assumptions for the single rate, here at 3%, 5% and 7% rates, but additional discussion has been provided by Manne and Stephan (1999).

The current policy decisions deal with near-term emission targets, or alternatively near-term emission prices. Figure 4 therefore presents the optimal hedging strategies for 2020, defined by the optimal emission levels and prices[6], for all assumption combinations. Since all these differing assumptions yield considerable different strategies, it remains unanswered whether the analysis can provide policy advice.

The different assumptions have obvious consequences. Higher discount rates shift more of the mitigation burden to the future, and shift the optimal emissions and prices along the cost curve. Capacity inflexibility increases the prices somewhat, without effect on optimal emissions in 2020. Taking the climate dynamics of CH_4 and N_2O appropriately into account lowers optimal emission levels, as hypothesized earlier, with also a slight effect on optimal prices.

The cost curve assumption, however, deserves special attention. Evidently higher abatement costs necessitate higher prices, but it is noteworthy how large the difference in optimal prices is between the low and high cost cases in 2020. The higher emission levels with the high-cost curves seem to

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[6] The term “prices” refers to the shadow value of CO_2. In the case with capital lifetime, the shadow value can differ from the marginal cost with which emissions are reduced. For gases other than CO_2, the GWP-weighted shadow value towards the temperature target can differ from the shadow value of CO_2, see Manne and Richels (2001) for further analysis regarding this.

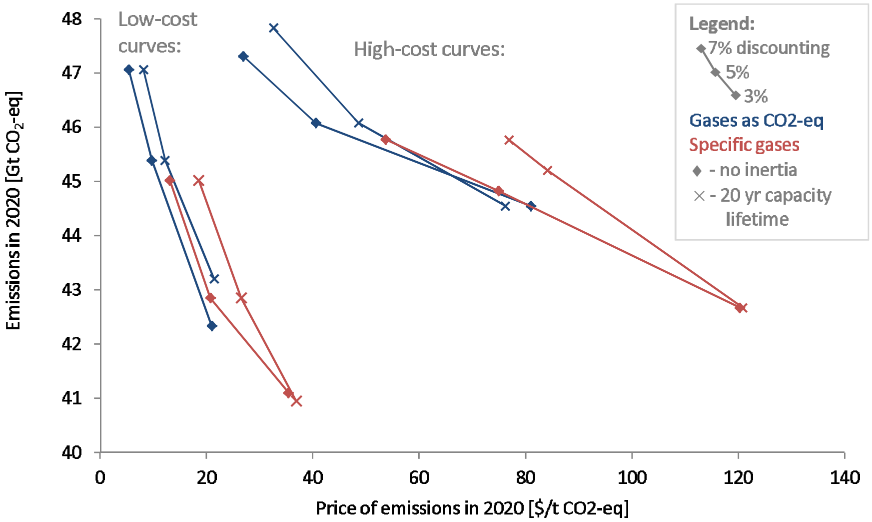

Figure 4: Emission pricing and emission levels in 2020 with optimal hedging strategies under different assumptions on reduction cost curves, discount rates, inertia of reduction measures and treatment of different greenhouse gases.

be, on the other hand, a mere artifact from the setup of cost curves. In the high-cost case, emissions lower than in the low-cost case are required between 2030 and 2070 in order to compensate the difficulty to reach negative emissions during the end of the century. With the current setup this is dominated by the difficulty of reaching even moderate reductions in 2020, although these two drivers need not be tied together. After all, the possibility of negative emissions in the distant future might not be connected to the cost curve of 2020, as has bee assumed in our low-cost and high-cost curves. Further research with added detail on the reduction possibilities is thus necessary.

5. Conclusions and discussion

Mitigation of climate change can be framed as a question of large-scale risk management. This paper intends to address one side of the issue, the cost risk of a temperature target under uncertainty on climate sensitivity. With analytical and numerical solutions to the problem, stochastic scenarios on optimal hedging strategies were presented.

As the most direct outcome, risk hedging against uncertainty in climate sensitivity necessitates more ambitious early emission reductions than what a deterministic approach would imply, a result that has been presented already earlier (Johansson et al., 2008; Syri et al., 2008; Webster et al., 2008). In addition, gradual learning on climate and sequential decision making bring about a vast range of possible emission pathways and optimal emission prices. Especially for long-term energy investments, the risk in emission prices might be of great importance.

The exact level at which either emissions or emission prices should be set for 2020 with an optimal risk hedging strategy, however, depends largely on the assumptions. The approach used in this paper, for example, assumes a single, global discount rate. This is in conflict with differing marginal productivities of capital between countries, but affects the hedging strategy significantly. Nevertheless, the discounting assumption for technical emission abatement costs rests on a more solid ground than the discounting of climate damages in cost-benefit analysis.

An even greater impact on near-term strategy arises from the emission reduction possibilities. On one hand, the long-term reduction potentials and costs translate to near-term actions via expected future emission prices according to equation (6). The prices reflect current and future reductions that are necessary to reach the temperature target also under worst-case realizations of climate sensitivity. On the other, near-term actions are guided by near-term reduction potentials. While these two factors were entangled in the assumptions of this paper, further research should strive to separate them. A potential approach would be to introduce uncertainty and subsequent learning also to the future cost curves, perhaps taking effects from technological learning also into account. Before these issues are addressed, decision support for global climate policy from such experiments might be too imprecise.

Indeed, the optimal emission reductions in 2020 across different assumption sets vary with a factor of two, while the largest of optimal emission prices is ten times higher than the lowest. This difference in the width of the optimal reduction and price ranges is also interesting. Should the result be of more general nature, it might shed light to the discussion on whether a price or quantity should be a preferred mode of control (Weitzman, 1974).

The sequential decision making approach could also be applied to answer where the temperature target should be set. A simple setting, similar to this paper, might consider only learning on climate sensitivity. Such approach might suggest that the temperature target should be adjusted to a higher level if climate sensitivity turns out to be high, since in that case also the cost of reaching the 2°C target will be high. A more comprehensive framework could also consider learning on adaptation costs and economic damages from climate change, although it might be challenging to make well-grounded specifications on when and under what circumstances new information on these would become available. Still, some critical aspects such as the discounting of future benefits and fat-tailed distributions for the damages, would remain unanswered.

The risk hedging and sequential decision making portrayed in this paper addresses the cost side of the whole cost-benefit framework, and also intends to provide policy support towards the 2°C target. Main insights of the paper frame how near-term and possible long-term actions should be balanced, given assumptions on possible learning and estimates on reduction possibilities. Accurate near-term policy guidance seems, however, be yet out of reach.

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References

Ackerman, F., DeCanio, S. J., Howarth, R. B., Sheeran, K., 2009. Limitations of integrated assessment models of climate change. Climatic Change 95 (3-4), 297–315.

Ackerman, F., Stanton, E. A., Bueno, R., 2010. Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE. Ecological Economics 69 (8), 1657 – 1665.

Azar, C., Sterner, T., 1996. Discounting and distributional considerations in the context of global warming. Ecological Economics 19 (2), 169 – 184.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S. H., Kyle, P., Smith, S. J., Thomson, A., Wise, M., 2009. 2.6: Limiting climate change to 450ppm CO_2 equivalent in the 21st century. Energy Economics 31, Supplement 2 (0), S107 – S120.

Ekholm, T., Soimakallio, S., Moltmann, S., Hhne, N., Syri, S., Savolainen, I., 2010. Effort sharing in ambitious, global climate change mitigation scenarios. Energy Policy 38 (4), 1797–1810.

Fuss, S., Johansson, D. J. A., Szolgayova, J., Obersteiner, M., 2009. Impact of climate policy uncertainty on the adoption of electricity generating technologies. Energy Policy 37 (2), 733–743.

Gurney, A., Ahammad, H., Ford, M., 2009. The economics of greenhouse gas mitigation: Insights from illustrative global abatement scenarios modelling. Energy Economics 31, Supplement 2 (0), S174 – S186.

Hammitt, J. K., Lempert, R. J., Schlesinger, M. E., 1992. A sequential-decision strategy for abating climate change. Nature 357 (6376), 315–318.

Johansson, D. J. A., Persson, U. M., Azar, C., 2008. Uncertainty and learning: Implications for the trade-off between short-lived and long-lived greenhouse gases. Climatic Change 88 (3-4), 293–308.

Knutti, R., Hegerl, G., 2008. The equilibrium sensitivity of the earth's temperature to radiation changes. Nature Geoscience 1 (11), 735–743.

Kolstad, C. D., 1996. Learning and stock effects in environmental regulation: The case of greenhouse gas emissions. Journal of Environmental Economics and Management 31 (1), 1–18.

Krey, V., Riahi, K., 2009. Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets-greenhouse gas mitigation scenarios for the 21st century. Energy Economics 31, Supplement 2 (0), S94 – S106.

Leach, A., 2007. The climate change learning curve. Journal of Economic Dynamics and Control 31 (5), 1728–1752.

Ljungqvist, L., Sargent, T., 2004. Recursive Macroeconomic Theory. MIT Press.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. Computational Management Science 5 (1-2), 7–40.

Loulou, R., Labriet, M., Kanudia, A., 2009. Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. Energy Economics 31, Supplement 2 (0), S131 – S143.

Manne, A., Stephan, G., 1999. Climate-change policies and international rate-of-return differentials. Energy Policy 27 (6), 309–316.

Manne, A. S., Richels, R. G., 1991. Buying greenhouse insurance. Energy Policy 19 (6), 543–552.

Manne, A. S., Richels, R. G., 2001. An alternative approach to establishing trade-offs among greenhouse gases. Nature 410 (6829), 675–677.

Nordhaus, W. D., 1991. To slow or not to slow: The economics of the greenhouse effect. The Economic Journal 101 (407), pp. 920–937.

Ruszczynski, A., Shapiro, A., 2003. Stochastic programming models. In: Handbooks in Operations Research and Management Science, 10: Stochastic Programming. North Holland, Ch. 1.

Syri, S., Lehtil, A., Ekholm, T., Savolainen, I., Holttinen, H., Peltola, E., 2008. Global energy and emissions scenarios for effective climate change mitigation-deterministic and stochastic scenarios with the tiam model. International Journal of Greenhouse Gas Control 2 (2), 274–285.

Tol, R. S. J., 2003. Is the uncertainty about climate change too large for expected cost-benefit analysis? Climatic Change 56 (3), 265–289.

van Vuuren, D. P., Stehfest, E., den Elzen, M. G., van Vliet, J., Isaac, M., 2010. Exploring image model scenarios that keep greenhouse gas radiative forcing below 3 W/m^2 in 2100. Energy Economics 32 (5), 1105 – 1120.

Webster, M., Jakobovits, L., Norton, J., 2008. Learning about climate change and implications for near-term policy. Climatic Change 89 (1-2), 67–85.

Weitzman, M. L., 1974. Prices vs. quantities. The Review of Economic Studies 41 (4), pp. 477–491.

Weitzman, M. L., 2009. On modeling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics 91 (1), 1–19.

ARTICLE II

Robustness of climate metrics under climate policy ambiguity

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Robustness of climate metrics under climate policy ambiguity

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ABSTRACT

A wide array of alternatives has been proposed as the common metrics with which to compare the climate impacts of different emission types. Different physical and economic metrics and their parameterizations give diverse weights between e.g. CH_4 and CO_2, and fixing the metric from one perspective makes it sub-optimal from another. As the aims of global climate policy involve some degree of ambiguity, it is not possible to determine a metric that would be optimal and consistent with all policy aims. This paper evaluates the cost implications of using predetermined metrics in cost-efficient mitigation scenarios. Three formulations of the 2 °C target, including both deterministic and stochastic approaches, shared a wide range of metric values for CH_4 with which the mitigation costs are only slightly above the cost-optimal levels. Therefore, although ambiguity in current policy might prevent us from selecting an optimal metric, it can be possible to select robust metric values that perform well with multiple policy targets.

1. Introduction

An active discussion has been going around the common metrics issue. The problem is to find proper weightings or indices with which to compare the climate impact of different greenhouse gases and radiatively active aerosols, each having different lifetimes and radiative efficiencies in the atmosphere. The use of climate metrics allows the aggregation of different forcers' emissions into a single quantity, and also determines how much each forcer's emissions should be reduced if an efficient climate policy would be pursued. Traditionally the comparison is against the climate impact of CO_2, with varying definitions on what the actual impact measure is. Given the long lifetime of CO_2 in the atmosphere, the choice of metric is most salient for short-lived species, such as black carbon, aerosols and particularly – given its share on global radiative forcing – CH_4.

Climate metrics have drawn considerable interest also in the climate policy arena (UNFCCC, 2012), as it e.g. affects countries' emission inventories and determines the role of short lived climate forcers in global climate policy. Currently, the Global Warming Potential with a 100 year timeframe (GWP_{100}) has been embedded into multiple policy frameworks, e.g. the Kyoto protocol. The GWP measures the integrated radiative forcing of a gas over a selected timeframe to that of CO_2. Another perspective for calculating the metrics that has gained particular attention is the Global Temperature change Potential (GTP), which compares the temperature changes after a given period after the emission, again e.g. after 100 years (Shine et al., 2005). A variant of this, here referred as dynamic GTP, uses a decreasing time-frame that targets warming in a given year – e.g. a year when a selected temperature limit is assumed to be reached – instead of a fixed horizon after the time of emission (Shine et al., 2007). Other proposed physical metrics include Integrated GTP (Peters

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et al., 2011), Forcing Equivalence Index (Wigley, 1998), and Temperature Proxy Index (Tanaka et al., 2009). Each metric has its own rationale of equating differing measures of climate impact between the gases. Therefore it is not possible to decide on the basis of science alone which metric should be used in climate policy.

Since climate change is not only physical, but also an economic problem, metrics based on economic reasoning have also been proposed. From an economic perspective, the metric reflects the valuation of a gas with regard to a selected economic problem setting. In reality this would be manifested as the market price for the gas; its optimal tax level or the price of emission allowance. Two separate approaches – based on how the mitigation problem is formulated – have emerged: the Global Damage Potential (Kandlikar, 1995) and Global Cost Potential (Manne and Richels, 2001).[1] Relationships between physical and economic metrics have been discussed by Tol et al. (2012).

The diversity of proposed metrics underlines a shortcoming inherent with the metrics concept. Regardless of how it is formulated, a single ratio cannot equate all the complex and dynamic consequences that different emission types induce. If the metric is set from one perspective, the climate impact is equal from that perspective only, but not with regard to some other measure of climate impact. A metric cannot therefore entirely equate all climatic impacts (Wigley, 1998; Smith and Wigley, 2000), and perhaps should not be used for that purpose. A single number or ratio is, however, necessary for multi-gas climate policy. The metric represents relative valuation of different gases, i.e. the optimal price ratio, which is a single number at any point of time.

The debate on metrics has mostly focused on the question whether the GWP_{100} is appropriate, occasionally also asking how the merits of a metric should be determined. No answer has emerged to the latter question, because this depends on political and value judgements and cannot be answered purely on scientific basis. Although it seems clear that the metric should reflect the aims of the policy it is meant to serve (Shine, 2009), the aims of global climate policy are not very accurately defined. From a scientific point of view, there is disagreement whether mitigation should be analysed as a cost–benefit question, or as a cost-effectiveness question with an external climatic target, for example the 2 °C target (see e.g. Ackerman et al., 2009; Yohe, 2009), and whether the externally set targets should include e.g. rate-of-change limits for temperature. This disagreement creates ambiguity both in what would be an optimal economic metric, and also in how the merits of different metrics should be assessed.

Several papers have assessed the economic impacts of using different metrics in climate change mitigation scenarios. Comparisons between GWP_{100} and a cost-efficient valuation has been provided by O'Neill (2003) and Aaheim et al. (2006) for a radiative forcing target, and by Johansson et al. (2006) for a temperature increase limit of 2 °C above the preindustrial level. In these studies, GWP_{100} increased mitigation costs from 2% to 4% relative to the cost-efficient valuation. Reisinger et al. (2012) used GWP_{100}, GTP_{100} and dynamic GTP in scenarios with a radiative forcing target, and reported the costs under GWP_{100} to be from 5% to 10% lower than with GTP_{100}, and from 4% to 7% higher than with dynamic GTP. The costs from several metric values for CH_4 have also been reported by Smith et al. (2013) under several radiative forcing targets.

The purpose of this paper is to extend this line of research with the consideration of climatic uncertainties and ambiguity over climate policy targets. The perspective is a cost-efficient approach to limit global mean temperature increase below 2 °C from the preindustrial level. To demonstrate the effect of ambiguity in climate policy, the paper uses three interpretations for the 2 °C target by including optional rate-of-change limits for temperature and risk-hedging against uncertainty over climate sensitivity. For each policy formulation, the paper considers the increase in mitigation costs due to the use of a predetermined metric, relative to the cost-efficient metric of that policy formulation. This analysis is done for selected physical metrics, as well as a wide range of arbitrary metric values for CH_4.

The paper focuses the metric between CH_4 and CO_2, since the two gases have very differing atmospheric characteristics and comprise a large part of current total radiative forcing. Throughout the paper, only metrics for pulse emissions are considered. From an economic or policy point of view, a metric for step emissions is not relevant, because an economic agent or political entity cannot commit to an infinitely long step emission. Also, the physical aspects of the metrics, i.e. how well the used concepts resemble the physical reality and what physical uncertainties are involved, have been left out of the scope.

The structure of the paper is as follows. The two economic metrics are first reviewed in Section 2, which also provides renewed and extended calculations compared to past literature. The section then concludes with a comparison between the physical and economic metrics. Section 3 calculates the cost of using selected physical metrics – as well as an arbitrary metric values for CH_4 – in three interpretations of cost-efficient 2 °C scenarios. Finally, the main conclusions of the analysis are discussed.

2. A review of economics-based metrics

The economic problem of climate change mitigation can be defined in two ways, and this also affects the economic valuation of different greenhouse gases. In the cost–benefit approach, the costs of mitigation and benefits from avoided climatic damages are balanced so that the marginal costs and benefits are equal. In this problem setting the relative values of gases are then defined by the marginal damage values that the emission pulses of different gases inflict. This metric is usually called Global Damage Potential (GDP) (Kandlikar, 1995, 1996) (see also Eckaus, 1992; Reilly and Richards, 1993).

Although cost–benefit analysis is theoretically well-grounded, the difficulties in estimating climate damages has led to the more simplified approach; that of pursuing a predetermined climate target in a cost-efficient manner. The cost-efficiency approach thus considers explicitly only the

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[1] Manne and Richels did not themselves use the term Global Cost Potential, but their approach was coined only later with this name.

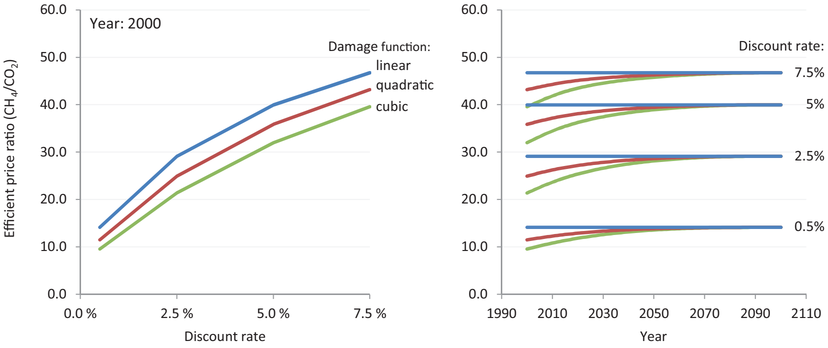

Fig. 1 – Estimates for Global Damage Potential for CH_4 with linear, quadratic and cubic damage functions; and four discount rates between 0.5% and 7.5%. Background temperature affects the Global Damage Potential with non-linear damages, hence the right side presents the GDP values for emissions arising at different years in a 2 °C scenario, while the left side presents detail for emissions arising in year 2000.

costs, while the benefits of mitigation are implicitly represented by a physical target, for example a limit on temperature increase or the rate of its increase. The valuation of emissions is then based on the marginal increase in costs of attaining the selected target, and is called the Global Cost Potential (GCP) (Manne and Richels, 2001).

Both approaches aim at an economically efficient solution, but give very different weights for valuing short- and long-lived gases. This section reviews both metrics; analyses the effect of necessary assumptions on the metrics values; and concludes with a comparison of some physical and economic metrics.

2.1. *Global Damage Potential*

An emission pulse has a time-varying impact on global mean temperature. Let us assume that the instantaneous damage to society relates to the temperature increase at that time with some increasing function. Then, given a background projection for temperature, a damage response may be calculated for a single emission impulse from the derivative of the damage function. Discounting the marginal damage response to its present value gives the social cost of that emission impulse. As a formula, for gas *i*, this is

$$\mathrm{NPV}_i = \int_0^{\infty} e^{-\rho t} \frac{\partial D(T(t))}{\partial T(t)} \frac{\partial T(t)}{\partial e_i(0)} \, dt \qquad (1)$$

where ρ is the discount rate, t is time, D the damage function, T the increase in global mean temperature, and $e_i(0)$ the emission of gas i at time zero. Finally, the ratio of social costs of two gases from (1) is the Global Damage Potential (Kandlikar, 1995, 1996), the appropriate climate metric from the cost–benefit perspective. A detailed analysis of GDP has been provided recently by Boucher (2012).

The actual level of damage function does not play a role in calculating the GDP – only the shape of the function. In the social cost ratio between two gases, any scaling factors between temperature and monetary damages cancel. After all, the GDP compares two relatively similar marginal damage responses to each other. Hence the GDP is determined mainly by the interplay of discounting and temperature response length of the gases, but also by the height of the temperature response and the functional form of the damage function.

For calculating the GDP, a background temperature projection that stabilizes to 2 °C by 2100 is assumed. The temperature responses following a pulse emission are calculated with the climate module of the TIMES Integrated Assessment Model (TIAM). This model is chosen to ensure consistency with the cost-efficiency calculations presented later in Sections 2.2 and 3. The module is based on the DICE model (Nordhaus, 2008), and is described briefly in Appendix A and in more detail by Loulou and Labriet (2008).

Using these assumptions, Fig. 1 presents estimates on GDP for CH_4 with discount rates ranging between 0.5% and 7.5%; and linear, quadratic and cubic damage functions. The damage is computed using a limited 1000 year horizon for the temperature response and damage, and for emission pulses arising from year 2000 to 2100.[2] The GDP for CH_4 is relatively small with discount rates close to zero, but rises steeply with higher discount rates, owing to the short lifetime of CH_4 relative to CO_2. The importance of the damage function's form decreases as the year 2100 approaches, as the temperature was assumed to stay constant at 2 °C after that, and as the temperature dependence of marginal damages then becomes equal with all damage parameterizations. Based on these results, the proper climate metric for CH_4

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[2] Note that with long time horizons and very low discount rates, the GDP metric depends highly on how a CO_2 impulse is assumed to remain in the atmosphere over future centuries. As an extreme example, using the CO_2 response function from Forster et al. (2007), an infinite time horizon and a zero discount rate, the social damage from a CO_2 emission impulse would be infinite, because the impulse is assumed to never be fully removed from the atmosphere. Hence, the GDP of other gases would be zero in this case. This effect is not as dramatic when using a 0.5% discount rate and the CO_2 impulse response of the TIAM climate module, and the present value of damages occurring after 1000 years – the time horizon for the numerical computations presented here – is negligible.

would be between 40 and 50 if the common 5% discount rate would be used, and the metric would remain relatively constant throughout the century if the 2 °C target is pursued. Lower discount rates would warrant lower metric values. The GDP values are well in line with e.g. those reported by Kandlikar (1996) and Boucher (2012).

2.2. *Global Cost Potential*

Due to the difficulty of applying cost–benefit analysis on climate change, climate policy has rather been formulated as a cost-efficient pursuit of selected climatic targets, such as the 2 °C target. Although the GDP partially sidesteps the problems involved in a full cost–benefit analysis, it might seem incoherent to use a cost–benefit based metric in a cost-efficiency problem. Hence, the metric might be also formulated based on the cost-efficiency setting. This approach is the Global Cost Potential, presented first by Manne and Richels (2001).

A cost-efficiency problem is based on a climatic target and an estimate on costs for emission reduction that are needed to attain the target. By minimizing the emission reduction costs, the optimization gives also the marginal costs of emissions as a result. The marginal costs reflect how much a marginal emission impulse of a given gas would increase the cost of attaining the future targets. Hence the marginal costs differ between gases, and the GCP is the ratio between the marginal costs of two gases. Estimating the GCP requires projections on future reduction costs, for example with the MERGE model by Manne and Richels (2001), and it is therefore somewhat more complicated than GDP. An approximation relying only on the discount rate and the year at which the temperature constrain becomes binding, has however been provided by Johansson (2012).

The GCP is dependent on what kind of a climatic target is selected. Manne and Richels (2001) presented GCP values of CH_4 and N_2O for warming limits of 2 °C and 3 °C over the 2000 level, and also by including an additional rate-of-change limit for temperature. Another important assumption is the discount rate (Johansson, 2012). A characteristic feature of the GCP is that the metric values vary over time. For a gas with short lifetime, such as CH_4, the value of the gas increases as the temperature approaches the limit. On the other hand, the rate-of-change limit – when binding – gives more weight to temperature changes in the near future, and hence increases the value of CH_4 considerably during the early half of the century.

The GCP estimates are calculated with a simple model that minimizes the net present value of global mitigation costs using a 5% discount rate and marginal abatement cost (MAC) curves estimated from Integrated Assessment Model results presented in past literature. A more detailed description of the model is provided in Appendix A. In the case with the rate-of-change, the limit was set to 0.125 °C/decade, effectively creating a temperature constraint that increases linearly from 2020 and reaches 2 °C by 2100. This is a very ambitious limit, and is chosen here to illustrate a policy with very ambitious early mitigation action.

A temperature limit can also be formulated as a risk-hedging problem. There is substantial uncertainty about climate sensitivity, and thus we do not know how deep reductions would be needed to stay below a selected temperature limit in the future. To embody this, the cost-efficiency problem under uncertainty can be solved by introducing sequential learning on climate sensitivity and sequential decision making on optimal emission reductions. This changes both the optimal reduction profile and the price ratios of different gases, as has been shown by Johansson et al. (2008). A description of the stochastic approach is provided briefly in Appendix A.

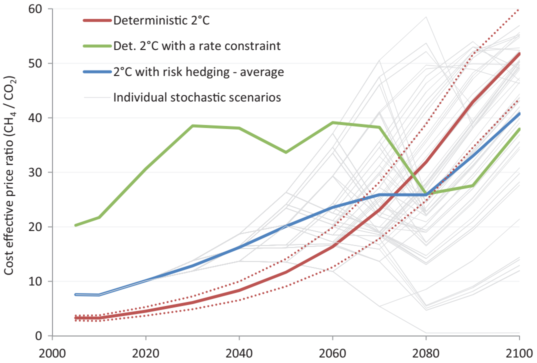

Fig. 2 – Global Cost Potential for CH_4 under either 2 °C warming limit, 2 °C and a rate-of-change limit, or a 2 °C limit with risk hedging against uncertainty on climate sensitivity. The dotted red lines correspond to the deterministic 2 °C scenario with 3% (lower) and 7% (upper) discount rates. The thin grey lines correspond to different scenario realizations in the stochastic setting, see Appendix A for details.

Calculations on the GCP for CH_4 in the deterministic and risk hedging cases are presented in Fig. 2. The deterministic settings is adapted from Manne and Richels (2001), and the stochastic settings is refined from Johansson et al. (2008). The effect of different discount rates is illustrated in the deterministic 2 °C case by varying the rate between 3% and 7%. The GCP estimates in Fig. 2 confirm that the GCP is indeed dependent on the climatic target that is to be acquired. Without the rate-of-change limit the GCP increases throughout the century, starting from rather low values and reaching values over 50 by 2100. Using such metric would, however, imply that no value is given to how fast the temperature increases. By including the rate-of-change limit the metric value is increased to vary between 20 and 40.

2.3. *A comparison of physical and economical metrics*

As the preceding sections presented, diverse values of economic metrics of CH_4 can be justified. Although both the cost–benefit and the cost-efficiency formulations address ultimately the same problem, they suggest very distinct metric values. Combinations of possible parameter values add to this variation.

As an illustrative comparison, Fig. 3 presents some variations of GDP and GCP, correspondingly from Figs. 1 and 2, alongside with selected physical metrics. These include the currently used GWP_{100} from Forster et al. (2007), GTP with 100 and 40 year timeframes, and dynamic GTP. The timeframes of

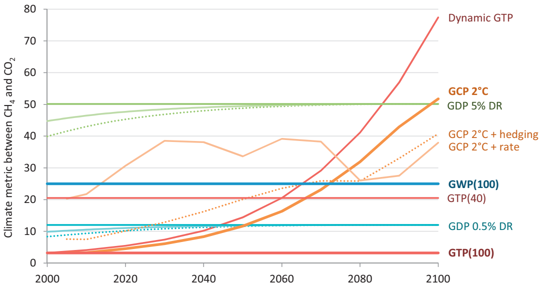

Fig. 3 – A comparison of different climate metrics for CH_4.

constant GTPs correspond to that used in the current GWP, and the average distance from 2020 to 2100, i.e. between the years that mitigation action is assumed to start and the time that the 2 °C target is assumed to become binding. Dynamic GTP with the target year at 2100 is chosen because – though being a purely physical metric – it resembles the GCP for a 2 °C target (Shine et al., 2007; Johansson, 2012). The target year of dynamic GTP is again set with the assumption that the temperature constraint becomes binding in 2100. The variations of GTP are calculated with the climate module used earlier for GDP and GCP.

Of the presented metrics, GTP_{100} indicates a considerably lower valuation for CH_4 than the other metrics. From an economic perspective, GTP_{100} is in line only with GDP with discount rates below 0.5%. GTP_{40} and GWP_{100} would correspond roughly to GDPs with discount rates of 2% and 2.5%, respectively, and be somewhat too low from the perspective of GCP with the chosen rate constraint. GDP with a 5% discount rate produces metric values that are primarily higher than with other approaches. Dynamic GTP and the GCP with a deterministic 2 °C limit are almost equal during the early half, but diverge during the later half of the century. However, this similarity is somewhat dependent on the discount rate used for calculating the GCP. See Fig. 2 for the impact of discount rate on GCP and (Johansson, 2012) for additional discussion. Metric values that increase over time – with varying levels of steepness – are supported mainly by dynamic GTP and GCP without a rate constraint. GDP with non-linear damages also exhibits such behaviour, but only to a modest extent.

Fig. 3 shows clearly how different approaches, policy formulations and parameterizations lead to widely varying metric values. Some approaches suggest relatively constant values; others highly time-varying values. For a single gas, as for CH_4 here, any given metric value may be supported by several approaches through the selection of suitable parameter values, as the similarity between GWP_{100} and GTP_{40} also indicates. Furthermore, selecting an optimal metric from one perspective or for one policy formulation would make the metric suboptimal from some other perspective.

3. The effect of metrics on cost-efficiency

As has been noted, the merits of a climate metric should be measured with regard to the policy it is intended to serve. Articles 2 and 3 of the United Nations Framework Convention on Climate Change (UNFCCC) – which can be regarded as the official formulation on the aims of global climate policy – state that measures to prevent dangerous climatic interference should be cost-efficient; precautionary action should be taken despite the lack of full scientific certainty; and that the timeframe of action should allow natural adaptation of ecosystems. Later, the Copenhagen Accord stated the limiting of global temperature increase below 2 °C as the explicit climatic target. This could be interpreted as an aim of attaining of the 2 °C target cost-efficiently, possibly including hedging against scientific uncertainty and rate-of-change limits. With this room for interpretation, there is still ambiguity in the policy description.

The problem setting might also be turned another way. How much worse an outcome would a given suboptimal metric result in, when compared to the optimal one of each explicit policy goal? If the benefits of finding the optimal metrics are small, there might be reasons external to the policy aims that would warrant the use of a suboptimal metric. Based on the above interpretation of the UNFCCC articles, this section investigates the cost implications of using predetermined metrics in scenarios that aim at cost-efficient attainment of the 2 °C target. Similar cost increase estimates have already been done for GWP_{100} by O'Neill (2003), Aaheim et al. (2006), Johansson et al. (2006) and also for GTP_{100} and dynamic GTP by Reisinger et al. (2012), but mainly for radiative forcing targets.

To complement these studies, this paper provides impact estimates for different interpretations of the 2 °C target by including also rate-of-change targets and hedging against uncertainty. Comparing the economic impacts of the metrics in widely different policy formulations gives a better understanding on the robustness of metrics. The selected metrics include GWP_{100},[3] GTP_{40}, GTP_{100} and dynamic GTP with 2100 as the target year. This spectrum of metrics is yet too narrow. To obtain more general results, the timeframes of metrics could be varied. Instead of this, generality is pursued by calculating the cost increase with any arbitrary metric value for CH_4.

3.1. *Physical metrics in cost-efficient scenarios*

The model and the problem settings are the same as in the GCP calculations of Section 2.2. A cost-optimizing model using marginal abatement curves for CO_2, CH_4 and N_2O is used to calculate cost-efficient scenarios with three targets: deterministic 2 °C scenarios with and without a rate-of-change constraint; and a stochastic 2 °C scenario with risk hedging against the uncertainty of climate sensitivity.

In addition to the cost-efficient solutions to each problem setting, sub-optimal solutions with predetermined physical

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[3] Note that the GWP_{100} metric value is based on Forster et al. (2007), and not on the climate module used in the cost-minimization model. The climate module is based on linearized versions of the radiative forcing formulas used in Forster et al. (2007), and a different model for the atmospheric lifetime of CO_2 (for details, see Loulou and Labriet, 2008). The 100-year GWP of CH_4, after accounting for indirect effects similarly to IPCC (2007), calculated with the used climate module is 23, i.e. slightly lower than the value given by Forster et al. (2007).

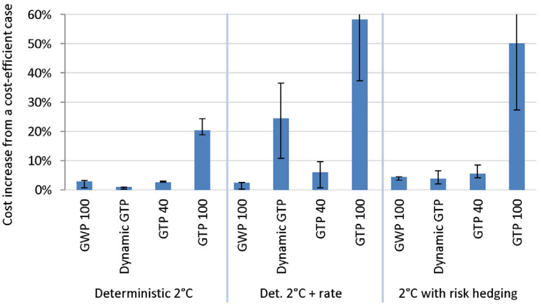

Fig. 4 – Cost increase from a cost-efficient case to a case with GWP_{100}, Dynamic GTP, GTP_{40} and GTP_{100} as the predetermined metric; under either a 2 °C warming limit, 2 °C and a rate-of-change limits, or a 2 °C limit with risk hedging against uncertainty on climate sensitivity. The blue columns represent the cost increase if a 5% discount rate is used, and the error bars indicate the increase range with 3% and 7% discount rates.

metrics are calculated, and the additional mitigation costs are then compared to the cost-efficient case. With the predetermined metrics, the model is free to choose the reductions for a basket of gases, with the relative prices – and hence the reduced amounts – of different gases being set down by the metric. In the cost-efficient case, the model may choose the reductions of the three gases individually. The analysed physical metrics – GWP_{100}, GTP_{40}, GTP_{100} and dynamic GTP – are defined as presented in Fig. 3. It is important to note that the target year for the dynamic GTP metric is set at 2100, which is the year when global mean temperature increase attains the 2 °C limit. Should the constraint become binding earlier or later in some given scenario setting, the target year should be adjusted accordingly.

Fig. 4 presents the mitigation costs relative to the cost-efficient case, in which no predetermined metrics are set, of each problem setting. Of the three metrics, dynamic GTP is the most cost-efficient in both deterministic and stochastic 2 °C scenarios. The near-optimality of the dynamic GTP in the deterministic case is understandable given its proximity with the GCP metric with 5% discounting in Fig. 3. GWP_{100} incurs only slightly higher costs than dynamic GTP in these two cases, but is the most cost-efficient if also a rate-of-change limit is considered. Very similar impacts result with GTP_{40}, which is obvious given its proximity with the GWP_{100} metric. GTP_{100} involves by far the highest costs in all settings. Results with a pattern similar to the deterministic 2 °C case for GWP_{100}, GTP_{100} and dynamic GTP, though by using radiative forcing targets, have also been presented by Reisinger et al. (2012). The cost increase for GWP_{100} in the deterministic 2 °C case is also similar to those reported by O'Neill (2003), Aaheim et al. (2006) and Johansson et al. (2006).

With the rate-of-change limit, GTP_{100} and dynamic GTP value CH_4 too low during the first half of the century, when the rate constraint bites the hardest and discounting has a smaller effect on the present value of costs. GTP_{100} is particularly inefficient in the rate-constrained and stochastic problems. Both settings require the fast temperature response of CH_4 reductions for effective mitigation, but GTP_{100} values CH_4 reductions far less than what the cost-efficient pricing implies.

3.2. *Using arbitrary metrics for CH_4*

The above results are still limited in perspective. The analysis covered only four metrics, and only two time horizons were considered. Including more timeframes for both metrics would be possible, but it is also possible to abstract from the physical reasoning behind the metrics and consider them merely as some agreed price ratios between gases, that are here assumed to remain constant over time. This approach gives a more general view on how the three cost-efficiency problems respond to changes in the metrics.

With only three greenhouse gases under consideration, the metric value for CH_4 is of most interest due to the similar atmospheric decay rates of CO_2 and N_2O. Based on this, we hold the metrics of N_2O at its GWP_{100} value and vary the metrics of CH_4 freely on a broad range, and then calculate the cost increase as in Section 3.1 for these arbitrary CH_4 metrics.

The mitigation costs relative to the optimum are presented for the three cost-efficiency problem formulations in Fig. 5. With each setting, there is a region of the predetermined CH_4 metric where all costs increase curves remain relatively flat, and are only modestly above the cost-optimal solution. The range is roughly between 20 and 40, but depends on the setting. If CH_4 valuation is close to zero, the costs rise sharply as the low-cost CH_4 reduction potential is disregarded, particularly in the rate-constrained and stochastic settings.

This cost increases are consistent with past studies. O'Neill (2003), Aaheim et al. (2006) and Johansson et al. (2006) all reported the cost of using GWP_{100} to range from 2% to 4% with deterministic climate targets of 550 ppm, 4.5 W/m^2 and 2 °C, respectively. This is very close to the 2 °C curve around CH_4 metric of 21 in Fig. 5. The point with a zero CH_4 metric on the 2 °C curve also corresponds well to van Vuuren et al. (2006), who reported a cost difference of 30–40% between CO_2-only and multi-gas mitigation scenarios with a range of models aiming at 4.5 W/m^2 radiative forcing target.

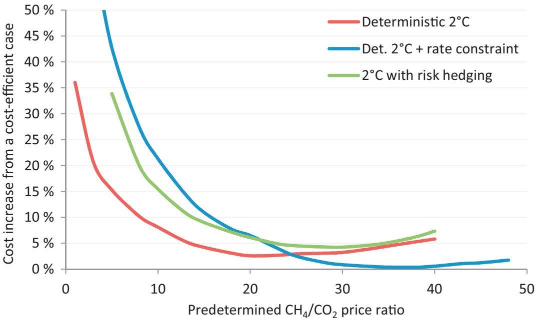

Fig. 5 – Cost increase from a cost-efficient case to a case with different predetermined price ratios between CH_4 and CO_2, under either a 2 °C warming limit, 2 °C and a rate-of-change limits, or a 2 °C limit with risk hedging against uncertainty on climate sensitivity.

The curves of Fig. 5 also imply that an increase in the price ratio from the optimal level has a smaller impact on the reduction costs than an equal decrease in the ratio. An analytical treatment for this phenomenon is provided below, but the overall reason is that with steeply rising marginal costs, a price increase affects the reduction levels less than a decrease in price, and thus the emissions deviate less from the optimum. By same feature the relative cost increase in the stochastic case exceeds the cost increase in the deterministic cases, as the predetermined price ratio is notably too low in some stochastic realizations.

3.3. *An analytical investigation on predetermined price ratios*

For an analytical examination, let us consider two gases with cost curves $C_1(r_1)$ and $C_2(r_2)$ dependent on the reduction levels r_1 and r_2. The cost curves have properties $C_i'(r_i) > 0$, $C_i''(r_i) > 0$ and $C_i'''(r_i) > 0$, i.e. that the marginal costs $C_i'(r_i)$ are a convex function of r_i. Under optimal reductions r_1^* and r_2^* the marginal rate of substitution (MRS) – i.e. the rate at which the gases may be substituted for each other to generate the same climatic response with regard to the cost-minimization problem – is the optimal price ratio between the gases, $MRS = C_1'(r_1^*)/C_2'(r_2^*) \equiv p_1^*/p_2^*$.

If the price[4] of gas 1 is now artificially raised from the optimum p_1^* by δp, emission reductions change by the amount δr. To keep the climatic impact unchanged, this is accompanied by a change of $MRS \cdot \delta r$ in the reduction of gas 2, assuming that δr is sufficiently small so that the substitution rate MRS remains essentially unchanged. The total costs, written as a function of the price change δp, are now

$$C(\delta p) = C_1(r_1^* + \delta r) + C_2(r_2^* - MRS\,\delta r) \tag{2}$$

Now, if the price is instead lowered by δp, the change in the reduction of gas 1 is δr_2. Because the marginal cost $C_1'(r_1)$ is assumed to be a convex function, the reduction level as a function of price is a concave function, and it follows that $\delta r_2 > \delta r$. The difference in costs between these two cases – that we either increase or decrease the price of gas 1 by δp – is given by $C(\delta p) - C(-\delta p)$. We can analyse this by a second-order Taylor polynomial

$$\begin{aligned} C(\delta p) - C(-\delta p) \approx{} & C_1'\delta r + \frac{C_1''}{2}\delta r^2 - MRS\,C_2'\delta r + MRS^2\,\frac{C_2''}{2}\delta r^2 \\ & - C_1'\delta r_2 - \frac{C_1''}{2}\delta r_2^2 - MRS\,C_2'\delta r_2 - MRS^2\,\frac{C_2''}{2}\delta r_2^2 \end{aligned} \tag{3}$$

Using the definition of MRS the first order elements cancel, and we find that

$$C(\delta p) - C(-\delta p) \approx \frac{1}{2}[(C_1'' + MRS^2\,C_2'')(\delta r^2 - \delta r_2^2)] < 0 \tag{4}$$

because all the derivatives are positive and $\delta r_2 > \delta r$. Hence, with very general assumptions on the forms of the cost curves, an increase in price of a gas from the optimal level increases the costs less than an equal decrease in its price.

4. Discussion and conclusions

In order to properly incorporate economics into a metric – and also to evaluate the economic impact from using a metric – the economic problem would have to be unambiguous and encompass everything we ultimately want to achieve. There is yet major disagreement on which approach and e.g. discount rate should be used when dealing with the climate change problem, and this disagreement seems insolvable for an indefinite amount of time. It is thus not possible to single out any economic method as "the right" way to determine the metrics. This is problematic, because the GDP and GCP approaches and their different parameterizations yield very diverse values and temporal profiles for the metrics.

This paper takes the approach of attaining the 2 °C target cost efficiently. However, in order to portray ambiguity in current policy formulation, the paper interprets the 2 °C target in three different ways. In calculating the cost impact from using selected physical metrics, the paper presents also sensitivity analyses with regard to discount rate choice.

If one climate target and discount rate can be singled out, it is possible to optimize the metric for that setting. In this case, even if the economically optimal metric could not be used or agreed on, an appropriately selected physical metrics can work as close approximations for the optimal metric. Based on the results presented in Fig. 4, dynamic GTP would be close to the cost-optimum under the deterministic 2 °C target with all assessed discount rates. The performance of dynamic GTP is, however, not as good if hedging against uncertainty in climate sensitivity is considered, and far from optimal if a rate-of-change target is considered. In the deterministic and hedging cases, the use of GWP_{100} and GTP_{40} involve costs that are very close to, and in the rate-of-change case considerably lower than those involved by the use of dynamic GTP.

If, however, a single target cannot be selected, it might be beneficial – in the sense of global mitigation costs – to select a robust metric that performs well with all possible, relevant climate targets. In the scope of this paper this seems possible. Although the optimal metrics differed notably between the three formulations of the 2 °C target, Fig. 5 exhibited a region of constant metric values for CH_4 where the mitigation costs are close to the optima of each target. In particular, constant metric values of CH_4 between 25 and 35 result in cost increases that are below 5% of the cost-efficient case with all three climatic targets. Of the considered physical metrics, GWP_{100} is at the low end of this range, and the timeframe of a GTP metric needs to be shorter than 40 years to fall into this range. What Fig. 5 also implied, is that is seems safer from the global costs point of view to overestimate rather than underestimate the metric value of CH_4. Whether this is a generic result – as the analytic investigation also suggested – or e.g. a feature of the model used in this paper, should be investigated further.

There are some caveats – as usual – that should be borne in mind when interpreting these results. The scenario model is based on MAC curves for CO_4, CH_4 and N_2O estimated from large-scale IAM results, and assumes that the emissions of these gases can be reduced independently from each other, and also from any other climatically important activity, such as aerosol emissions. The interactions between different

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[4] Regarding the prices, we might assign gas 2 as a numeraire, fixing its price to 1. Now, interpreting the gases 1 and 2 correspondingly as CH_4 and CO_2, the price p_1 actually is the price ratio between CH_4 and CO_2, just as in Fig. 5.

emission sources in the economic system can, however, be noteworthy. For example, reductions in CO_2 can induce reductions in the emissions of CH_4 and SO_2 (see respectively Smith et al., 2013; Smith and Wigley, 2006, for further analysis). These interactions are likely to affect particularly the cases with a low predetermined price ratio between CH_4 and CO_2, and cases with a rate-of-change target, owing to the large short-term forcing impact of CH_4 and SO_2. The MAC curves themselves and assumed emission baselines are also a source of uncertainty for the results. Assumptions for mitigation potential – either hard limits or steeply rising marginal costs – will affect especially the cases with a rate-of-change target and the stochastic scenarios with high realized values of climate sensitivity. Also whether emission reduction measures with negative costs are included in the emission baseline or the MAC curves can have an impact on the results. Although these caveats seem unlikely to alter the main findings of this paper, the accuracy of the results could be improved by using a larger-scale IAM and a more detailed climate model in subsequent research.

There are a number of conclusions for subsequent research and discussion around the metrics issue. Ambiguity in policy formulation prevents us from selecting an optimal metric. If the metric is based on the economic optimization for one problem formulation, it can be highly suboptimal from some other perspective or formulation. Given that an optimal metric might not exist, the choice of metric might not be free from some level of arbitrariness. Instead of optimizing the metric, a metric that performs well with different problem formulations that hold relevance, could be described and agreed on. Such a robust metric is likely to be more resilient to possible adjustments in future policy objectives.

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Appendix A. Model description

The model used is a linear cost-optimization model with predetermined baseline emissions and global marginal abatement cost (MAC) curves estimated from past mitigation scenario literature (Calvin et al., 2009; Gurney et al., 2009; Krey and Riahi, 2009; Loulou et al., 2009; van Vuuren et al., 2010). The model covers emissions of CO_2, CH_4 and N_2O, and assumes that these emissions can be reduced independently from each other, and with full temporal flexibility.

The climate module is the same as in the TIMES Integrated Assessment Model (TIAM), and uses a three-reservoir model for CO_2 concentration (atmosphere, surface ocean and deep ocean), first-order decay for CH_4 and N_2O, and two-reservoir model for temperature (mixed layer and deep ocean). The climate module is documented in detail by Loulou and Labriet (2008). The model uses 10 year time steps, and the calculated scenarios extend to 2200 in order to avoid end-of-horizon effects at the end of current century. The objective is to minimize the present value of global mitigation costs, discounted with a 5% rate, so that the temperature limit holds.

The stochastic scenarios assume uncertainty and gradual learning for the climate sensitivity parameter (Cs), and allow sequential decision making in 10 year periods to accommodate the new information on Cs. The recurrent learning forms a stochastic process, and in this problem formulation the expected discounted costs are to be minimized. The initial probability distribution is a discretized version of the symmetric distribution of Knutti and Hegerl (2008). Starting from 2030, either the highest or lowest possible value of Cs at that moment of time is excluded from the distribution every 10 years, until the true value of Cs is known with certainty in 2080. This is consistent with the results from a Bayesian learning model by Webster et al. (2008), and much more gradual process than former mitigation scenarios with uncertainty and learning on Cs (Syri et al., 2008; Johansson et al., 2008; Webster et al., 2008). The information process then forms a binomial lattice with 64 possible paths, and 7 possible end-states. As emission reductions are optimized sequentially, the emission levels and marginal costs of emissions form also 64 possible paths. The realization of an optimal CH_4 metric in each realization is depicted with grey lines in Fig. 2.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.03.006.

REFERENCES

Aaheim, A., Fuglestvedi, J.S., Godal, O., 2006. Costs savings of a flexible multi-gas climate policy. Energy Journal 27 (Spec. Iss. Nov.) 485–501.

Ackerman, F., DeCanio, S.J., Howarth, R.B., Sheeran, K., 2009. Limitations of integrated assessment models of climate change. Climatic Change 95 (3–4) 297–315.

Boucher, O., 2012. Comparison of physically- and economically-based CO_2-equivalences for methane. Earth System Dynamics 3 (1) 49–61.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S.H., Kyle, P., Smith, S.J., Thomson, A., Wise, M., 2009. 2.6: limiting climate change to 450 ppm CO_2 equivalent in the 21st century. Energy Economics 31 (Suppl. 2) S107.

Eckaus, R.S., 1992. Comparing the effects of greenhouse gas emissions on global warming. The Energy Journal 13 (1) 25–36.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R.V., 2007. Changes in atmospheric constituents and radiative forcing. In: Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom/New York, NY, USA.

Gurney, A., Ahammad, H., Ford, M., 2009. The economics of greenhouse gas mitigation: insights from illustrative global abatement scenarios modelling. Energy Economics 31 (Suppl. 2) S174.

Johansson, D.J.A., 2012. Economics- and physical-based metrics for comparing greenhouse gases. Climatic Change 110 (1–2) 123–141.

Johansson, D.J.A., Persson, U.M., Azar, C., 2006. The cost of using global warming potentials: analysing the trade off between CO_2, CH_4 and N_2O. Climatic Change 77 (3–4) 291–309.

Johansson, D.J.A., Persson, U.M., Azar, C., 2008. Uncertainty and learning: implications for the trade-off between short-lived and long-lived greenhouse gases. Climatic Change 88 (3–4) 293–308.

Kandlikar, M., 1995. The relative role of trace gas emissions in greenhouse abatement policies. Energy Policy 23 (10) 879–883.

Kandlikar, M., 1996. Indices for comparing greenhouse gas emissions: integrating science and economics. Energy Economics 18 (4) 265–281.

Knutti, R., Hegerl, G.C., 2008. The equilibrium sensitivity of the earth's temperature to radiation changes. Nature Geoscience 1 (11) 735–743.

Krey, V., Riahi, K., 2009. Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets-greenhouse gas mitigation scenarios for the 21st century. Energy Economics 31 (Suppl. 2) S94.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model. Part I: Model structure. Computational Management Science 5 (1–2) 7–40.

Loulou, R., Labriet, M., Kanudia, A., 2009. Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. Energy Economics 31 (Suppl. 2) S131.

Manne, A.S., Richels, R.G., 2001. An alternative approach to establishing trade-offs among greenhouse gases. Nature 410 (6829) 675–677.

Nordhaus, W., 2008. A Question of Balance, Weighing the Options on Global Warming Policies. Yale University Press, New Haven/London.

O'Neill, B.C., 2003. Economics, natural science, and the costs of global warming potentials. An editorial comment. Climatic Change 58 (3) 251–260.

Peters, G.P., Aamaas, B., Berntsen, T., Jan, S., 2011. The integrated global temperature change potential (iGTP) and relationships between emission metrics. Environmental Research Letters 6 (4) 044021.

Reilly, J., Richards, K., 1993. Climate change damage and the trace gas index issue. Environmental & Resource Economics 3 (1) 41–61.

Reisinger, A., Havlik, P., Riahi, K., van Vliet, O., Obersteiner, M., Herrero, M., 2012. Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. Climatic Change 1–14.

Shine, K.P., 2009. The global warming potential-the need for an interdisciplinary retrial. Climatic Change 96 (4) 467–472.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B., Stuber, N., 2007. Comparing the climate effect of emissions of short- and long-lived climate agents. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1856) 1903–1914.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change 68 (3) 281–302.

Smith, S.J., Karas, J., Edmonds, J., Eom, J., Mizrahi, A., 2013. Sensitivity of multi-gas climate policy to emission metrics. Climatic Change 117 (4) 663–675.

Smith, S.J., Wigley, T.M.L., 2000. Global warming potentials: 1. Climatic implications of emissions reductions. Climatic Change 44 (4) 445–457.

Smith, S.J., Wigley, T.M.L., 2006. Multi-gas forcing stabilization with Minicam. The Energy Journal Special Issue 3, 373–392.

Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H., Peltola, E., 2008. Global energy and emissions scenarios for effective climate change mitigation-deterministic and stochastic scenarios with the TIAM model. International Journal of Greenhouse Gas Control 2 (2) 274–285.

Tanaka, K., O'Neill, B.C., Rokityanskiy, D., Obersteiner, M., Tol, R.S.J., 2009. Evaluating global warming potentials with historical temperature. Climatic Change 96 (4) 443–466.

Tol, R., Berntsen, T., Oneill, B., Fuglestvedt, J., Shine, K., 2012. A unifying framework for metrics for aggregating the climate effect of different emissions. Environmental Research Letters 7 (4) .

UNFCCC, 2012. Report on the workshop on common metrics to calculate the carbon dioxide equivalence of greenhouse gases. Tech. Rep., UNFCCC Subsidiary Body for Scientific and Technological Advice.

van Vuuren, D.P., Stehfest, E., den Elzen, M.G., van Vliet, J., Isaac, M., 2010. Exploring image model scenarios that keep greenhouse gas radiative forcing below 3 W/m^2 in 2100. Energy Economics 32 (5) 1105.

van Vuuren, D.P., Weyant, J., de la Chesnaye, F., 2006. Multi-gas scenarios to stabilize radiative forcing. Energy Economics 28 (1) 102–120.

Webster, M., Jakobovits, L., Norton, J., 2008. Learning about climate change and implications for near-term policy. Climatic Change 89 (1–2) 67–85.

Wigley, T.M.L., 1998. The Kyoto Protocol: CO_2, CH_4 and climate implications. Geophysical Research Letters 25 (13) 2285–2288.

Yohe, G., 2009. Toward an integrated framework derived from a risk-management approach to climate change. Climatic Change 95 (3–4) 325–339.

ARTICLE III

Effort sharing in ambitious, global climate change mitigation scenarios

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Effort sharing in ambitious, global climate change mitigation scenarios

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ABSTRACT

The post-2012 climate policy framework needs a global commitment to deep greenhouse gas emission cuts. This paper analyzes reaching ambitious emission targets up to 2050, either -10% or -50% from 1990 levels, and how the economic burden from mitigation efforts could be equitably shared between countries. The scenarios indicate a large low-cost mitigation potential in electricity and industry, while reaching low emission levels in international transportation and agricultural emissions might prove difficult. The two effort sharing approaches, Triptych and Multistage, were compared in terms of equitability and coherence. Both approaches produced an equitable cost distribution between countries, with least developed countries having negative or low costs and more developed countries having higher costs. There is, however, no definitive solution on how the costs should be balanced equitably between countries. Triptych seems to be yet more coherent than other approaches, as it can better accommodate national circumstances. Last, challenges and possible hindrances to effective mitigation and equitable effort sharing are presented. The findings underline the significance of assumptions behind effort sharing on mitigation potentials and current emissions, the challenge of sharing the effort with uncertain future allowance prices and how inefficient markets might undermine the efficiency of a cap-and-trade system.

1. Introduction

The ambitious climate change mitigation targets considered currently require global participation in the mitigation effort in the post 2012-period. Article 3.1 of the United Nations Framework Convention on Climate Change (UNFCCC) requires that the mitigation effort should be shared between the parties "on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities". In order to reach a global solution, the equity issue has to be solved. Each country has to have the impression that it is treated equitably relative to the others in order for it to participate.

The question of what is actually equitable is ambiguous, and Article 3.1 is thus open to interpretations. As an example, Ringius et al. (1998) lists the following equity concepts:

- Egalitarian—equal emissions per capita.
- Sovereign—equal reductions from, e.g., 2000.
- Horizontal—equal net change in welfare, e.g. in GDP.
- Vertical—effort dependent on ability.
- Equal responsibility—effort based on historical emissions.

In addition to equity, to achieve economic efficiency the emissions should be mitigated where least costly. Solutions to the conflict between equity and efficiency include cap-and-trade systems or harmonized emission taxes. Under perfect markets without uncertainty, the approaches should produce the same outcome. The equity issue can then be dealt with either the allocation of tradable emission allowances or the redirection of tax revenues. Due to a more simpler setting, this paper analyzes a global cap-and-trade system.

In a perfect market setting the allocation of emission allowances is merely a financial compensation. The parties are free to trade allowances and their actions are guided solely by the market price of allowances, not by how much the party initially owns allowances. Therefore in principle the mitigation costs of the parties could be adjusted through the allocation without affecting the actual mitigation measures.

The level to which the global emissions should be reduced is obviously debatable. However, as were shown by Manne and Stephan (2005), under certain conditions, the optimal level of abatement for different countries does not depend on the

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allocation of allowances. Therefore the overall abatement level and equity issues can be separated and analyzed on their own.

Given an overall emission limit, effort sharing deals with the distribution of limited emission allocations to the parties. The effort sharing process and tools used should be reliable, understandable and transparent in order to build confidence in the process. The resulting allocations, however can, and moreover should, be analyzed with more sophisticated if less transparent models.

This paper focuses on the equity of effort sharing with two exogenously assumed reduction targets that would stabilize greenhouse gas atmospheric concentrations to 485 ppm CO_2-eq and 550 ppm CO_2-eq by the end of the century. A simple and transparent tool Evolution of Commitments (EVOC) (Höhne et al., 2006) tool is used to calculate the allocation of emissions, which are then used in long-term energy-climate scenarios produced with ETSAP-TIAM (Loulou and Labriet, 2008; Loulou, 2008), a more sophisticated integrated assessment model. Though transparently documented, the TIAM may be seemingly opaque due to its size and complexity.

The stance of vertical equity with respect to economic burden from mitigation is taken here, reflecting the ‘‘respective capabilities’’ stated in Article 3.1. Then the effort sharing rule should allocate higher mitigation costs (relative to GDP) for wealthier countries, measured e.g. in terms of GDP per capita, much in the same sense as progressive taxation taxes more those with higher income. The mitigation costs considered include direct mitigation costs, changes in energy trade, allowance trade and the value of lost demand due to price elasticity; but disregard indirect macroeconomic costs, damage costs and possible benefits from avoided climate change.

Numerous mitigation scenario studies have already been made. Past studies have, however, often considered only CO_2 or higher stabilization levels for atmospheric greenhouse gas concentrations than what can currently be seen as relevant (Fisher et al., 2007). Also, a number of studies investigating the effort sharing have been conducted. The studies have, however, analyzed the effort sharing only in terms of allocated emissions and by comparing them to GDP, historical emissions or population (Miketa and Schrattenholzer, 2006; Vaillancourt and Waaub, 2004), taken only CO_2 into account (Persson et al., 2006; Russ et al., 2005), or used a simplified model with marginal abatement curves (MACs), as e.g. den Elzen et al. (2005, 2007) with the FAIR model. An exception from these, though, is den Elzen et al. (2008b), which evaluates two effort sharing rules with the FAIR model using updated MAC curves, and including also detailed analyses with the energy and land use models of IMAGE. Studies with general equilibrium models have also been carried out (Böhringer and Welsch, 2004; Peterson and Klepper, 2007) providing light on the macroeconomic effects of mitigation measures, though with less detail on specific mitigation measures.

This paper intends to address these shortcomings with a threefold purpose. First, the attainability of ambitious mitigation targets, -50% from 1990 levels, for all Kyoto-gases until 2050 are analyzed while also exploring possible bottlenecks for further mitigation. Second, the mitigation scenarios are used to evaluate two effort sharing rules, also extending the analysis of effort sharing from past studies with regard to the equitability issue. Given the varying sectoral distribution of emissions across countries, the explicit reporting of the mitigation measures in the scenarios is also significant for effort sharing. Third, challenges in effort sharing are also analyzed, including imperfect allowance markets and consideration of uncertainties.

The paper is structured as follows. Section 2 describes the models for producing the emission allocations and the energy-climate scenarios along with some main assumptions. Section 3 first outlines the main mitigation measures in the scenarios, then focuses on the main economic outcomes both in global and regional scale, and finally assesses the equity of effort sharing. In Section 4 the relevant uncertainties, two cases of allowance market imperfections and the importance of assumptions behind the effort sharing are considered. Last, Section 5 draws up conclusions and discusses the main findings.

2. The models and scenario assumptions

Two separate models were used in this study. First, EVOC, a transparent but simplified effort sharing tool of Ecofys GmbH, is used to quantify the emission allocation with the Triptych (Phylipsen et al., 1998) and Multistage (den Elzen et al., 2006) effort sharing regimes. Future energy-climate scenarios with the two reduction targets are then analyzed with the more sophisticated but complex ETSAP-TIAM, a global integrated assessment model of the TIMES family. Although the TIAM is well documented, fully consistent and the input data can be made available upon request, the vast size and relative complexity of the model may render the model non-transparent to the reader.

2.1. EVOC

The effort sharing is based on Triptych and Multistage calculations from EVOC (Höhne et al., 2006). These effort sharing approaches were chosen as subjects as the Triptych approach might provide a good balance between simplicity and detail, and Multistage might provide a relevant ”ladder” for developing countries to join. EVOC contains collections of data on emissions from several sources and future projections of relevant variables from the IMAGE implementation of the IPCC SRES scenarios. As emission data vary in its completeness and sectoral split, EVOC combines data from the selected sources and harmonizes it with respect to the sectoral split.

Future emissions are based on IMAGE projections of parameters, such as population, GDP (PPP), electricity consumption and industrial value added. As IMAGE projections are available only for 17 world regions, EVOC de-aggregates these data by combining it with historical values. Finally, the user can set the parameters of several effort sharing rules in order to calculate emission allocations. The main parameters used in this study are provided in the electronic annex for the paper in the publisher’s website.

2.1.1. Triptych

The Triptych approach was originally developed for sharing the CO_2 mitigation effort between the EU member states using three sectors: power sector, the internationally operating energy-intensive industry and the domestically oriented sectors (Phylipsen et al., 1998), but has been updated thereafter to contain more countries (Groenenberg et al., 2001), sectors and greenhouse gases, and recently also to have multistaged commitments (den Elzen et al., 2008a).

The emission target for each sector is calculated with given assumptions on the reduction potentials in the sector. The Triptych version 6.0 that was used in the study is documented by Phylipsen et al. (2004). This version uses six sectors: Electricity, Industry, Fossil fuel production, Domestic, Agriculture and Waste. The electricity and industry sectors use parameters on efficiency, structure and income levels to calculate the emission limits. Domestic, and waste sectors use a single convergence level, given in terms of $tCO_2-eq/capita$, to which the emissions of countries converge by a given year. This is to reflect the converging living standards and practices in different countries. For fossil fuel production and agriculture, reduction levels from the baseline are assumed. In addition to this sectoral differentiation, Triptych also uses a rough income categorization with some parameters to distinguish countries with different levels of affluence.

The emission allocation of a country is then the sum of the sectoral targets. It is though critical to note that only the country level target is binding, not the sectoral targets on which the country level target is based on. Thus Triptych is not a sectoral approach per se, but uses sectoral mitigation potentials to arrive on a more accurate estimate on how much reductions are feasibly attainable in a given country and leaves the country free to choose how to pursue its target. As the Triptych approach takes into account the sectoral distribution of emissions, and even though it uses in principle uniform sectoral potentials across all countries, it has the ability to accommodate national circumstances better than most other simplified approaches. It also explicitly allows for economic growth and improving efficiency in all countries and aims to put internationally competitive industries on the same level.

2.1.2. *Multistage*

As the name suggests, in a Multistage approach the countries participate in several stages with differentiated levels of commitment (den Elzen et al., 2006). Each stage has stage-specific commitments with countries graduating to higher stages when they exceed certain thresholds (e.g. emissions per capita or GDP per capita), and all countries agree to have commitments at a later point in time. For this study, thresholds and commitments based on per capita emissions with four stages were applied.

Least developed countries start at stage 1, which carries no commitments. At stage 2 the countries commit to sustainable development, in practice moderate reductions, e.g. 10%, from the baseline scenario. Stage 3 would involve moderate absolute targets, e.g. more stringent targets than in stage 2. The target could now also be only positively binding, so that the country could sell allowances if it reaches its target but would not be penalized if it did not. Finally, at stage 4 the country faces substantial reduction targets. As time progresses, more and more countries enter the stage 4.

In this study, the concept of Multistage effort sharing is, however, slightly abused, as the cap-and-trade system was assumed to bind all countries. Instead, the countries without binding commitments receive emission allocations according to their baseline emissions, but are then free to mitigate emissions and sell the excess allowances for profit. If this were not the case, the mitigation policy regime would lose its effectiveness.

2.2. *ETSAP-TIAM*

The energy and emission scenarios in the study were formed with the TIAM (TIMES Integrated Assessment Model) (Loulou and Labriet, 2008; Loulou, 2008), which is based on the TIMES (The Integrated MARKAL-EFOM System) modelling methodology (Loulou et al., 2005a), both developed under the IEA's Energy Technology Systems Analysis Program (ETSAP). The TIMES family of models are bottom-up type linear partial equilibrium models that calculate the market equilibrium through the maximization of the total discounted economic surplus with given external end-use demand projections. The models assume perfect markets and, in their basic form, unlimited foresight for the calculation period.

The TIAM models the whole global energy system with 15 geographical regions. Main assumptions concerning the energy system, future energy technologies, potentials and other mitigation options in the model are described by Syri et al. (2008). All Kyoto-greenhouse gases (CO_2, CH_4, N_2O and F-gases) from all anthropogenic sources are covered by the model, although emissions from land use change were not considered in this study.

The energy consumption is based on external projections of the growth of regional GDP, the population and the volume of various economic sectors, which have been harmonized to the IMAGE implementation of four SRES scenarios that are used in EVOC, ensuring consistency between the models. Inclusion of four different energy demand scenarios—marked as A1, A2, B1 and B2—provides also perspective on the effect of different assumptions on energy demand in the future.

In order to satisfy the demands, the model contains estimates on energy resources, a vast number of technology descriptions for energy production, transformation and end use, and a number of other elements, such as user-defined constraints. The flows and prices of energy commodities, including international trade for energy and emission allowances, are calculated endogenously by the model.

The model also uses price-elasticity for energy end-use demand in the mitigation scenarios, so that final energy demand reacts to changing energy prices compared to the baseline scenario. The demand elasticity for changes in energy prices was assumed to be moderate, around -0.2 for most demands and around -0.4 for aviation and maritime transport, which were assumed to be more affected by changes in energy use prices. These values are very similar to the values used by e.g. Loulou et al. (2005b) or Persson et al. (2006) with similar models. Due to this elasticity, the model can take macroeconomic feedbacks into account in a limited manner, and allows the model to reach the emission targets with lower costs than with inelastic demand. A sensitivity analysis on this by Persson et al. (2006) indeed confirmed this, and suggested that there might be also considerable regional variation in the effect of elasticity on mitigation costs. Therefore further work on the issue might be appropriate.

The model also includes a simplified climate module (Syri et al., 2008; Loulou and Labriet, 2008) that calculates changes in radiative forcing and global mean temperature with the resulting emissions. The module uses three reservoirs for CO_2 in the biosphere, first-order decay models for CH_4 and N_2O, and two heat reservoirs for calculating the temperature change. F-gases are converted into CO_2 equivalents while calculating the concentrations.

2.3. *Main scenario assumptions*

In addition to the technological and resource assumptions made in the TIAM model, assumptions on socio-economic development and the effort sharing itself are obviously important. As has many times been previously noted, e.g. in Riahi et al. (2007), the abatement effort is very dependent on the baseline scenario. With higher energy demand and emission projections, it is harder and costlier to meet a stringent emission target. Four different economic and population growth projections from the IMAGE implementation of the SRES scenarios (IPCC, 2000) were used consistently in both EVOC and TIAM. The growth of global GDP varies in the scenarios from 2.3% to 3.6% p.a. between 2000 and 2050 with regional growth rates being higher for developing and lower for developed countries. The projections were used to project the end-use energy demand in the baseline scenarios, to which the mitigation scenarios were compared to in order to calculate the mitigation costs.

Main characteristics of the two reduction targets considered are presented in Table 1. The targets were assumed to be globally binding from 2020. For calculating the resulting concentrations, radiative forcing and mean temperature increase (using 3 °C

Table 1
The implications of the two emission targets used.

Concentration in 2100	485 ppm	550 ppm
Emissions from 1990 in 2020	+20%	+30%
Emissions in 2020 (Gt CO_2−eq)	37.1	39.5
Emissions from 1990 in 2050	−50%	−10%
Emissions in 2050 (Gt CO_2−eq)	15.4	28.2
Rad. forcing in 2100 (W/m^2)	3.0	3.6
Temp. increase in 2100 (°C)	1.8	2.1

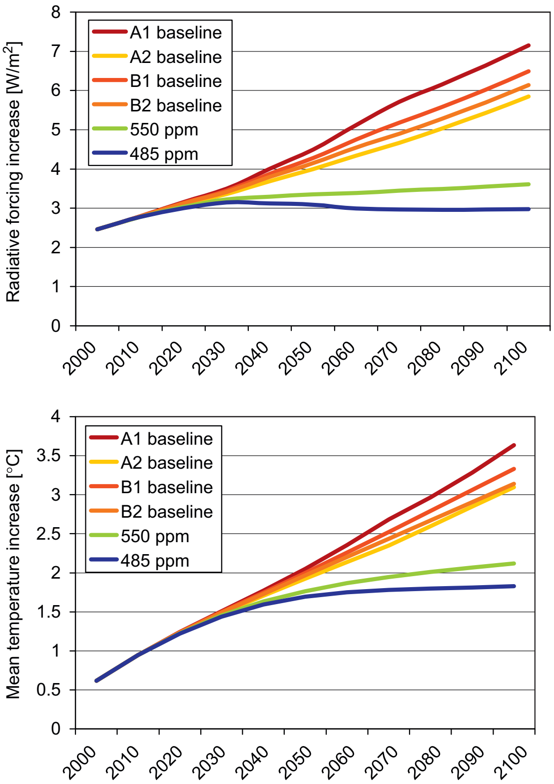

Fig. 1. Increase in radiative forcing (W/m^2, top) and global mean temperature (°C, bottom) in the four baseline scenarios and with the two mitigation scenarios.

climate sensitivity) up to 2100, the emission target of 2050 was assumed constant for the period between 2050 and 2100. If further reductions would be made post-2050, though, concentrations below 485 and 550 ppm would be attainable by 2100.

The more stringent target falls in the high end of IPCC Category I of stabilization levels (Fisher et al., 2007). It overshoots first to 505 ppm CO_2−eq in 2030 before declining to levels around and below 490 ppm, as can be seen in Fig. 1. The figure also presents the global mean temperature increase in baseline and reduction cases. With the 485 ppm target the temperature stabilizes during the century, whereas with the 550 ppm target it is still increasing in 2100 and would probably stabilize around 2.5 °C later on.

It is, however, critical to note that the measures in the scenarios do not affect land use change and forestry emissions. An undisturbed baseline scenario was assumed for deforestation, thus increasing the overall CO_2 emissions and concentrations. As the focus here is on effort sharing, and as the uncertainties of both deforestation emissions and afforestation measures are very large, it was natural to disregard these.

Fig. 2 presents the emission allocation, relative to 2000 emissions, in 2020 and 2050 for the 15 different countries or country groups in TIAM. The bars present the median of the four economic growth scenarios. The approaches allocate, respectively, 10–50% reductions for Annex I in 2020 and 60–95% reductions in 2050. Non-Annex I regions may increase their emissions up to 2020 by varying amounts, whereas in 2050 only the least developed regions receive allocations above their 2000 emission levels. Also it can be noted that the Multistage approach generally allocates more emissions to the least developed countries in 2050 than Triptych.

3. Scenarios

3.1. Emissions and mitigation measures

Of all the eight different mitigation scenarios created, the moderate growth B2 scenarios with both reduction targets are used for illustrating the mitigation measures. Fig. 3 portrays the emission profiles in both cases, separately for combustion and process emissions. As can be seen from Fig. 3, the electricity sector provides the largest cost-efficient mitigation potential. Also large emission reductions are carried out in the industrial sector and a number of measures also in the other sectors. Below is a list of main measures in five sectors:

- Electricity: Phase-out of coal; strong adoption of wind power and biomass; slight increase in hydro and nuclear from baseline; gas and coal with CCS.
- Industry: Phase-out of fossil fuels, especially coal; CCS; biomass, also combined with CCS; N_2O from chemical industries; blended cements replacing clinker.
- Transportation: Fuel efficiency; natural gas on heavier road vehicles; later hydrogen or electricity.
- Residential and commercial: The energy mix shifting to electricity and heat; efficiency; considerable potential on waste CH_4.
- Agriculture: Limited low-cost potential in all categories; extensive reductions challenging e.g. in cattle and rice paddy CH_4 and soil N_2O.

3.1.1. Electricity and industry

Emission reductions in electricity production and industry are perhaps the most straightforward and extensively studied. Phase-out of coal and other fossil fuels, or their use in conjunction with CCS, would contribute to the most of the emission reductions. Also, sustainably grown bio-energy with CCS could provide negative emissions.

Most electricity generating technologies, such as wind power, nuclear energy and biomass, are mature and already in the market. In the medium-long term, the only technology currently still in the demonstration phase is CCS. In 2050, however, there would be a need for novel production technologies as fusion power, though being very costly, emerged in 2050 in the scenarios, especially with the 485 ppm target.

Changes and improvements in industrial processes, such as increased use of steel scrap or inert anodes in aluminium smelters, would also contribute to the reductions. Blended cement and clinker kilns with CCS could be used in cement production. Also, N_2O emission reductions using thermal destruction and catalytic

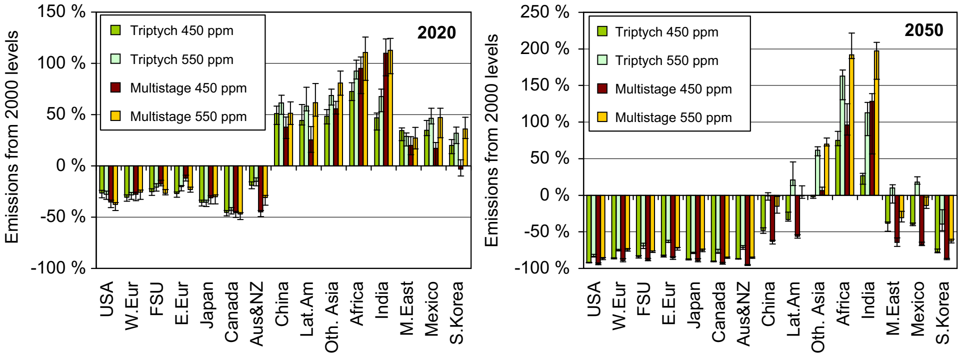

Fig. 2. Emission allocation, relative to 2000 emissions, with the Triptych and Multistage effort sharing approaches and two reduction targets in 2020 (left) and 2050 (right). The error bars correspond to the range of values with four baseline scenarios.

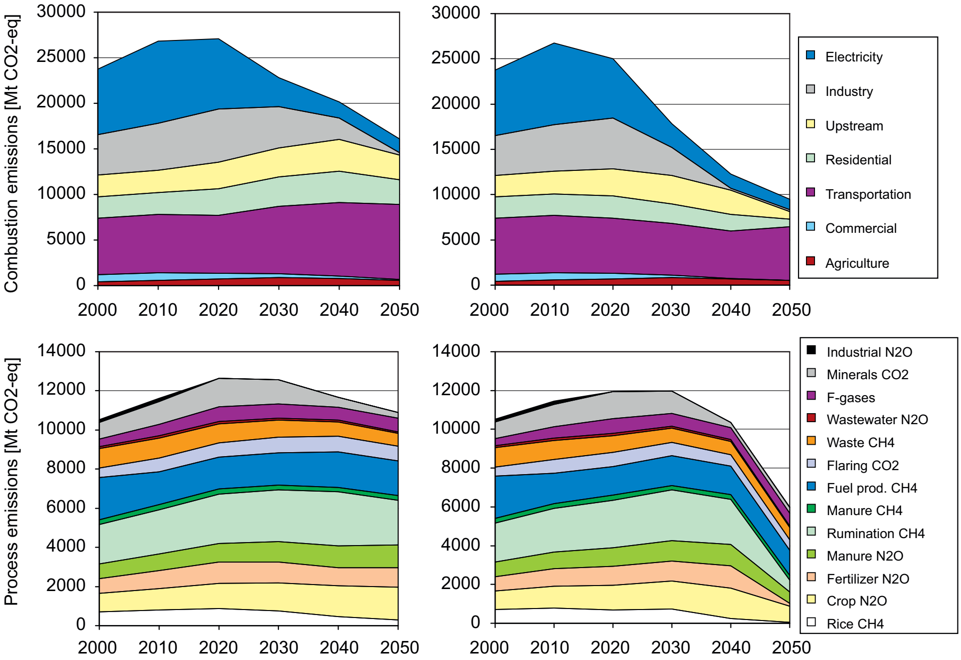

Fig. 3. Global greenhouse gas emissions with the 550 ppm (left) and 485 ppm (right) mitigation targets, split between combustion (top) and process-based (bottom).

reduction, respectively, in adipic and nitric acid industries are one of the first mitigation measures taken.

The total energy consumption in industry is reduced by roughly 8% in 2020 compared to the baseline due to better energy efficiency, leaving total industrial output down 2–3% from the baseline due to the demand price-elasticity. The rising carbon price affects production in the long run, and industrial production is on average 12% below the baselines with the 485 ppm target in 2050. With a 2% annual growth rate in industry output, this would equal a rather small 0.25% reduction in the annual growth rate.

3.1.2. Transportation

In road transportation deep reduction through a shift to natural gas, electricity/hydrogen and biofuels (when sustainably produced) should be feasible. Rising demand could however turn the decreasing trend in road transportation emission again to a rise by 2050 even with the low-emission technologies.

International transportation—especially aviation—might also pose more difficulties. Even though the fuel efficiency has improved in aviation, development extrapolated from the historical pace is not sufficient to stabilize emissions with the projected growth in aviation demand (Macintosh and Wallace, 2009). Clearly, then, if the emissions are deemed to decrease, also the demand has to decrease to some extent.

Studies and demonstrations with liquid hydrogen and biofuels (Fischer–Tropsch kerosene) as alternative aviation fuels have been conducted. Both fuels, however, have their difficulties. Hydrogen airplanes involve large technical and operational challenges due to the low volumetric energy density and the need for pressurized cryogenic tanks. The Fischer–Tropsch process is technologically mature and the product resembles fossil kerosene. The challenge with biofuels is, however, of price and quantity. The baseline final energy demand for aviation and shipping equalled roughly 60 EJ/a in 2050. As the required primary energy would be higher, it might prove hard to increase sufficiently the bioenergy supply—roughly at 130 EJ/a in the 485 ppm scenarios in 2050—even though the rising allowance prices might render biofuels competitive.

Due to these challenges, the technologies were excluded from the scenarios, and, as a result, the level of transportation emission remains relatively constant throughout the 485 ppm scenario.

3.1.3. *Agriculture*

Important mitigation potential exists in agriculture, often in the form of improved management practices. Mitigation measures have been analyzed for example in the EMF-21 study (DeAngelo et al., 2006), on which the mitigation measures in the TIAM model are mostly based on. The applicability of most measures is, however, only partial, and agricultural emissions tend to continue their growth in the reduction scenarios.

When very stringent emission targets, such as -50% reductions from 1990, are pursued, also agricultural emission have to be reduced considerably. If the potentials of technological and management options do not improve substantially from those assessed in DeAngelo et al. (2006), a shift towards less emitting agricultural products, e.g. cattle to poultry and swine and rice to other cereals, might be necessary.

With sufficiently high allowance prices this might happen directly through the market mechanism. As an example, assuming emissions of 1.5 t CO_2–eq/head/a (IPCC, 2006) for beef cattle and 200 kg meat yield after two years, an allowance price of 500$\$_{2000}$/t CO_2 would increase the producer price by 7.5$\$_{2000}$/kg meat. Similarly, taken the default emission factor of 1.3 kg CH_4 /ha/d for rice paddy (IPCC, 2006) and a production of 4 t rice/ha/a (FAO, 2009), the producer price would increase by 1.2$\$_{2000}$ /kg rice due to the emissions. Being roughly 2–5 and 10 times higher than the producer prices in 2000 (FAO, 2009), respectively, for cattle meat and rice, price increases of this magnitude might cut consumption considerably and shift it to lower emitting substitutes.

As the emission sources are very dispersed and mostly concentrated on rural areas of less developed countries, it is harder to control the emissions and effectively introduce better practices. Also, it is important to note the major uncertainties and dependences on local conditions with agricultural emissions, especially concerning N_2O.

A very important source of potential mitigation measures, reduced deforestation and afforestation, were not considered in the scenarios. As the estimates both on emissions from deforestation and mitigation options are very uncertain, these emissions and mitigation measures might distort the analysis of effort sharing substantially. On the global scale, the exclusion of these measures, however, increases the mitigation costs in the scenarios, perhaps even drastically.

3.2. *Mitigation costs*

The main issue in effort sharing is how to divide the global mitigation costs between the countries. Clearly, an important factor here is the total level of costs. The effect of different baseline scenarios and reduction targets on the mitigation costs has been noted in previous studies (e.g. Riahi et al., 2007). This arises from different demand levels for end-use commodities and the system costs in the baseline scenario.

An often used measure of economic burden is the mitigation costs, i.e. the difference in energy system costs between baseline and mitigation scenarios, divided by the projected global GDP. Fig. 4 portrays this measure on global scale in 2020 and 2050 for a spectrum of mitigation targets and four socioeconomical scenarios. The more ambitious end of the reduction targets equals the 485 ppm mitigation target and the more lax the 550 ppm target, the targets between being linear interpolations of the 485 and 550 ppm targets.

As the economic burden of mitigation is shared through the allocation and trade of emission allowances, the price of allowances is critical for effort sharing. Fig. 5 portrays the average price of allowances between 2020 and 2050 in the scenarios with both mitigation targets. As can be seen from the figure, the price is projected to rise steeply after 2030 with the tightening emission limits, especially with the 485 ppm target.

3.3. *Effort sharing*

Fig. 6 presents regional mitigation and emission trade costs in 2020 and 2050. A numerical table with additional details is

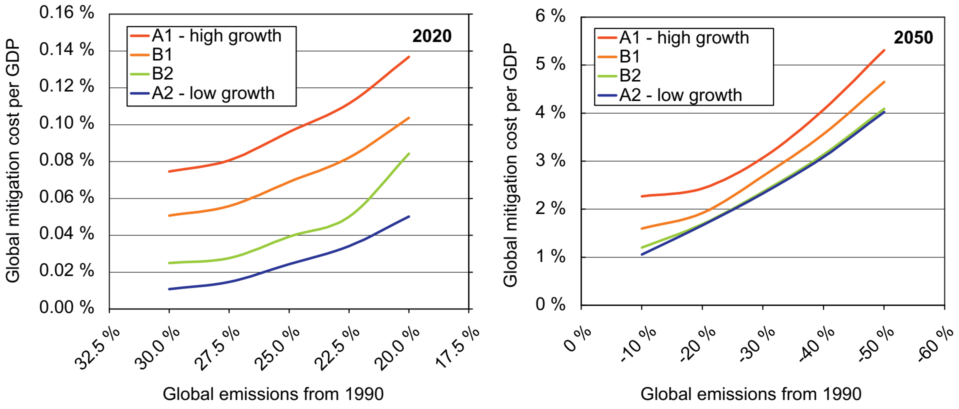

Fig. 4. Global mitigation costs relative to global GDP (*Y*-axis) in 2020 (left) and 2050 (right), with the different economic growth scenarios and emission reduction targets (relative to 1990 emissions, *X*-axis).

provided in Appendix A. Both effort sharing rules allocate costs for Annex I countries in 2020 (with the exclusion of Eastern Europe), costs around zero for more developed non-Annex I countries, and gains for least developed countries as a result of selling emission allowances. In 2050, Annex I countries, especially Australia and Russia (as a part of FSU) with the 485 ppm target, face relatively high costs. Also most non-Annex I countries face positive costs, and only India and Africa are able to gain financially from the effort sharing. The costs for Annex I regions are generally doubled with the 485 ppm target in 2050 compared to the 550 ppm target. A clear outlier from the overall pattern with all effort sharing rules is Middle East, the situation of which is analyzed briefly later.

For most regions the most important factor in the costs is allowance trade. Other factors include increased investment costs, reductions in fuel and operation costs and welfare losses as demand adjusts to higher energy prices. The volume of allowance trade can be substantial for some regions, especially in 2050 with the 485 ppm target when allowance prices are very high. The largest net seller in 2050 was India, which was able to sell allowances for from 1 Gt CO_2−eq (Triptych 485 ppm) to 4 Gt CO_2−eq (Multistage 550 ppm). Assuming a price of 500$/t, as an example, India would annually gain from 1% to over 10% of its baseline GDP from allowance sales in 2050, depending on the baseline. This would obviously have drastic impacts on the global economic system. For comparison, India's current account balance has been between -2.5% and 1.5% of GDP since 1980.

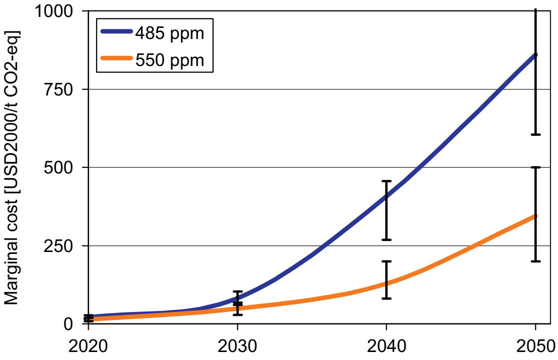

Fig. 5. Marginal costs of emission allowances ($\$_{2000}$/t CO_2-eq) in the scenarios. The error bars correspond to the range of values with four baseline scenarios.

As the Article 3.1 of the convention implies, the developed nations should take a lead in the mitigation effort. In order to assess the effort sharing in the light of the vertical equity principle, the regional mitigation costs were compared to the projected GDP per capita figures. Besides being equitable on a broad level, effort sharing should obviously be coherent by allocating similar costs for equally wealthy countries. An equitable and coherent effort sharing should then put the countries on an up-sloping line or a curve in the GDP per capita—mitigation cost plane. The slope of the curve should then be the subject of debate, that is, how much the more wealthy nations are seen to be responsible of taking on the costs.

In order to build more perspective, two very opposing effort sharing regimes are also portrayed in addition to Triptych and Multistage. An egalitarian approach, equal emissions per capita, has often been supported by developing countries. On the other hand, a grandfathering approach would be in line with the sovereign equity principle and favor the developed countries.

Fig. 7 portrays the regional mitigation costs against their GDP per capita projections, for 2020 and 2050 and both reduction targets. The figure includes also smoothed averages using Gaussian kernel smoothing to give better view on the overall equitability of each effort sharing regime.

Middle East, being an outlier from the overall pattern, was excluded from the kernel smoothing procedure. The mitigation costs in Middle East arise to a large extent from lower revenues from oil trade, resulting from a lower exports and oil price compared to the baseline scenarios, from 8% to 25% depending on the baseline and emission target, a phenomenon noted also by den Elzen et al. (2008b). Middle East is, however, a very heterogeneous group and the more wealthy oil-exporting countries, notably Saudi Arabia, Emirates, Kuwait and Qatar, constitute a relatively large share of both oil production and GDP in the region but only a small share of population, thus distorting the comparison between wealth and mitigation costs for Middle East.

As can be seen from Fig. 7, the differences between Triptych and Multistage in 2020 are relatively minor and fall between Per capita and Grandfathering approaches. The costs distribute equitably in the spirit of Article 3.1 with Triptych and Multistage approaches, with least developed regions having small negative costs, resulting from allowance sales, and developed regions having positive costs. While both approaches have a good coherence in costs vs. wealth, Triptych slightly outperforms Multistage in this sense. As was initially assumed, Per capita is very favorable to the least developed regions and Grandfathering for the developed.

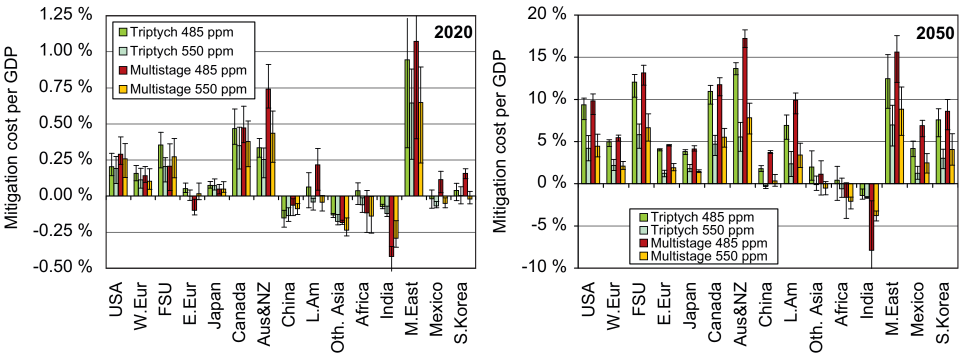

Fig. 6. Regional mitigation costs relative to their baseline GDP in 2020 (left) and 2050 (right). The error bars correspond to the range of values with four baseline scenarios.

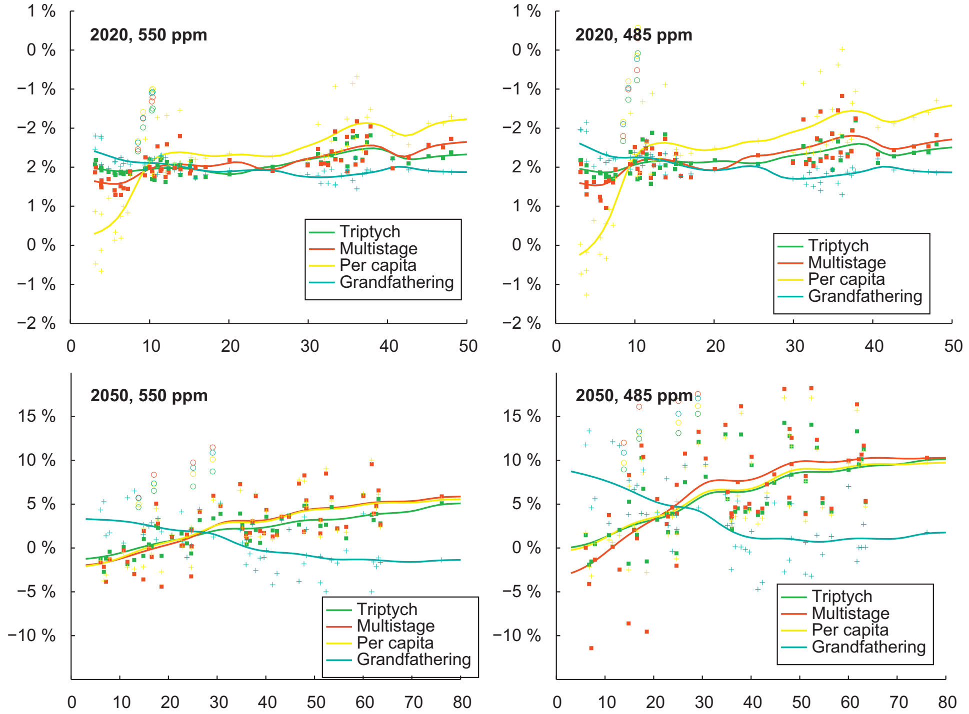

Fig. 7. Regional mitigation costs relative to GDP (y-axis) against regional GDP per capita (1000$\$_{2000}$(PPP)/cap/a, x-axis), with four effort sharing rules and two mitigation targets in 2020 and 2050. Each dot or cross represents a single region with one of the four economic scenarios used. The solid lines are average values calculated with gaussian kernel smoothing. Middle East, marked with circles, has been excluded from the smoothed lines.

In 2050 the Triptych, Multistage and Per capita approaches produce very similar results on average, but Triptych exhibits some differences from the other two in the regional scale. As the emission converge to given emission per capita levels in the Multistage by 2050, the results between Multistage and Per capita approaches are very similar also in the regional level. However, Multistage is even more beneficial for least developed regions than the Per capita approach with the 485 ppm target, as some countries are still below the fourth stage threshold.

In the Triptych approach the sectoral emission converge to either "low" or "near-zero" levels (electricity, fossil fuel production and industry) or to given per capita levels (other sectors). Agriculture can also be included in the latter category, as the targets are defined as reductions from baseline emissions, which in turn are driven by population growth. This explains the similarity of Triptych and Per capita approaches, as a large share of the emissions allowances is allocated in per-capita term, especially with the 485 ppm target.

In terms of coherence Triptych again outperforms the other approaches clearly with the 550 ppm target in 2050, but not quite so with the 485 ppm target. This is again explained by the dominance of per-capita based sectoral targets, which is greater with the 485 ppm target. The coherence of Triptych is based on its ability to take into account the sectoral distribution of emissions in different countries, and thus also the countries' mitigation abilities. If the allowances are allocated mostly in per-capita terms, as with the 485 ppm target, coherence deteriorates.

3.4. *Comparison to other studies*

Comparison of the results to previous studies using different models reveals the importance of background assumptions used. Different studies can be distinguished with regard to the model used, baselines, available mitigation potentials, emission targets and effort sharing rules used.

Two different studies (van Vuuren et al., 2007; den Elzen et al., 2008b), using the IMAGE system in slightly different scenario settings, provide a good reference point. The emission levels, somewhat above 20 Gt CO_2-eq in 2050, fall between our 485 and 550 ppm targets. The marginal costs in den Elzen et al. (2008b) were between 125 and 270\$/tCO_2-eq, which is generally lower than the range with our 550 ppm scenarios. The global costs were quite similar, around 1–2.5% of global GDP in 2050. The marginal and global costs in van Vuuren et al. (2007) with B2 fall into both of these ranges.

The differences in costs relative to the stringency of the emission target were attributed mostly to the assumptions on non-CO_2 mitigation and bioenergy supply potentials. The non-CO_2 potentials in the IMAGE model are based on an extension of the EMF-21 results (Lucas et al., 2007), and include rather optimistic estimates compared to those in the TIAM model. Also, bioenergy supply was limited to 500 EJ/a in den Elzen et al. (2008b), which is roughly four times larger than in our scenarios. Estimates both on bioenergy and non-CO_2 mitigation potentials are very uncertain, as was also acknowledged by den Elzen et al. (2008b). These assumptions have, however, a significant impact on the results, especially when deep emission reductions are assessed.

A comparison to Riahi et al. (2007), a mitigation scenario study using the MESSAGE model, is more difficult as the costs are reported only in terms of system costs and GDP losses, which is not directly translatable to the mitigation costs per GDP measure. However, an earlier study (Rao and Riahi, 2006) explores scenarios aiming at 4.5 and 3 $\mathrm{W/m^2}$ radiative forcing targets by 2100 with multi-gas strategies. Although the radiative forcing targets equal those attained in the scenarios presented here, the emission profiles are very different with emissions exceeding 30 Gt $\mathrm{CO_2-eq}$ in 2050 in the MESSAGE scenarios and declining more later on. As a result, the marginal costs of emissions are also substantially lower in 2050, slightly above 100\$/t $\mathrm{CO_2}$-eq, but reach levels around 750\$/t $\mathrm{CO_2-eq}$ by 2100.

The optimal profile of emission reductions is debatable, and cost-optimizing models such as TIMES and MESSAGE tend to postpone mitigation measures due to discounting if e.g. a radiative forcing or a temperature target is given instead of fixed annual caps. This can be also seen in a previous study with the TIAM modelling system (Syri et al., 2008), which investigated the optimal strategy for limiting global mean temperature increase below 2 °C by 2100. The optimization resulted with emissions around 30 Gt $\mathrm{CO_2-eq}$ in 2050, a level substantially higher than used in this study. However, as was also found by Syri et al. (2008), if stochastic optimization is used in the face of uncertainty in the climate sensitivity parameter, an optimal risk-hedging strategy would be to limit emissions to around 20 Gt $\mathrm{CO_2-eq}$ by 2050 in order to satisfy the 2 °C target. This result is therefore much in favor of targets lower than e.g. in Rao and Riahi (2006).

With regard to effort sharing, the results were compared to den Elzen et al. (2008b), which assessed Multistage and Contract and Converge effort sharing approaches. Even though having lower global mitigation costs, the patterns on how the cost is distributed is relatively similar to ours. Developed countries receive higher costs and least developed Sub-Saharan Africa and South Asia negative costs in 2050. Also, the countries under the former Soviet Union (FSU) region and Middle East fall outside the general pattern with higher costs, the former especially with Multistage effort sharing.

4. Challenges in effort sharing

Even if the effort can be shared in theory in a predetermined way, there are reasons why the economic burden might not distribute as planned. Perhaps the most evident is uncertainty in mitigation costs and the future price of allowances. In addition to this, the allowance market might not be perfect, which has been assumed in the analysis above, and this is analyzed in the case of transaction costs and imperfect participation to the market.

Also, the allocation of emission allowances is based on estimates on current emissions and sectoral mitigation potentials in the Triptych approach, but these parameters are not very well known. Although this uncertainty does not affect the analysis and methods used in this study as the allocation was taken as given, the allocation is obviously critical in defining the regional costs.

4.1. Imperfect markets

Two cases of market imperfections were considered to illustrate possible market-based hindrances for effort sharing. The first case introduces transaction costs in allowance trading, inhibiting the efficient functioning of markets. In the second case, a large net seller of allowances refuses to sell allowances to the market. Both cases were assessed in 2020 with the B2 growth scenario, 550 ppm mitigation target and Triptych effort sharing.

The introduction of transaction costs to the allowance market results with a situation where the sellers' and buyers' marginal abatement costs differ by the amount of the cost introduced. The cost might arise from numerous reasons, including imperfect information, market frictions or the faulting of the pricing mechanism, e.g. due to speculation. Some actors also might find it difficult or costly to trade in the market and monetary exchange rates might distort the efficiency of the market on a global scale. Also, volatile prices provide an incentive for risk averse hedging strategies that are somewhat costlier.

Due to the large number of potential sources, transaction costs are hard to quantify or forecast. To analyze its effect on the market, a quantification is, however, needed and as a rough guess a 10\$/t $\mathrm{CO_2-eq}$ transaction cost was imposed to the markets. This can be seen as a moderate increase to the allowance price of 15\$/t in 2020 in the setting without transaction costs. The cost reduced both the volume of emission trading by 20%, increased the costs of allowances by 23% (including the transaction cost), and doubled the global mitigation costs.

In the other case considered, a large net seller was assumed to refrain from trading its allowances. This can be conceptually contrasted from a scenario with limited participation in the overall mitigation effort, which has been analyzed previously e.g. by Edmonds et al. (2008). Even though all countries might comply with quantitative emission targets, there exists a risk that they will not participate in the allowance market in an efficient manner. China was chosen for this role for illustrative purposes, as it was the largest net seller of allowances in 2020 with Triptych effort sharing. It is also a large country holding slightly over 20% of all allowances with the Triptych allocation and might also hold relevant market power in practice.

In theory, a country cannot gain financially by restricting its allowance trading. Such action can be however easily justified. China faced some 40% increase in electricity prices and 90% increase in coal use costs when engaged with the global allowance markets in 2020. Coal and electricity make up over half of China's total final energy consumption in the baseline and over 80% in industry. Therefore, major political pressure might emerge against participating in the emissions trade if residents and companies were faced with steep increases in energy prices and were not compensated with the revenues from selling the allowances. Solutions to this dilemma might include using some of the emission trade revenues to subsidize clean energy production or consumption or a fragmented distribution of allowances to different actors in the allowance market.

On the global level, the setting resulted in one-third higher price for emission allowances compared to the basic setting, and a doubling of global mitigation costs. In contrast a surplus, though small, of allowances in China rendered their price to zero. In this scenario China loses its revenues from emissions trading but gains slightly on energy prices. Even though the total cost is slightly less than in the baseline, it is—as theory suggests—higher than in the case where China is selling its allowances.

4.2. Uncertainties

Uncertainties relevant for effort sharing arise from the baseline scenario, direct mitigation costs (technological and resource uncertainties) and allowance prices. Of these, the first was—to some extent—included in the analysis above with four baselines.

Technological and resource uncertainties affect in a simplified sense the marginal abatement curve (MAC) of a country. The effect on effort sharing is might be, however, small, as most technologies affect all countries. Then, a change in the costs or potential of a given technology affects effort sharing with countries that are more dependent on that technology than other countries. Such findings have been presented by den Elzen et al. (2005), where a second set of MAC's in the FAIR model raised uniformly the costs of all regions, although den Elzen et al. (2008b) noted that a specific technology's cost, CCS's in their case, might affect some countries more. The marginal mitigation cost is, however, also the basis for the price of allowances.

Allowance prices might also carry additional uncertainty due to market imperfections as was suggested in Section 4.1. The uncertainty in future allowance prices has important implications on the attainability of equitable effort sharing. The allowances have to be allocated to the countries in advance, and their value can be observed only later on.

As the price varies from 20% to 50% around the average between the scenarios with different baselines, and as the allowance trade might constitute a large share of region's mitigation costs, the price variability might affect the regional mitigation costs to a large extent. As the allowance trade costs are second order results from the model, they are more uncertain than most other results presented. However, with a given effort sharing regime, the amount of allowances a country buys or sells is relatively stable across the scenarios. In contrast, the price is very dependent on the background growth scenario. Uncertainties on marginal mitigation costs are in turn much larger for the more ambitious 485 ppm mitigation scenario, in which more unconventional measures have to be taken in order to reach the emission target.

4.3. Estimates of current emissions

Inventories or statistics on current emissions are far from perfect and subject to uncertainties, especially in the case of developing countries. Several organizations are providing emission estimates. Parties to the UN-FCCC are obliged to report their emission inventories, for Annex I parties annually and for the developing countries on a less frequent basis. The IEA publishes a global emission inventory from fuel combustion based on the energy statistics it gathers, supplemented with non-combustion emission estimates from the Emission Database for Global Atmospheric Research (EDGAR). Also, US-EPA has estimated global non-CO_2 emissions.

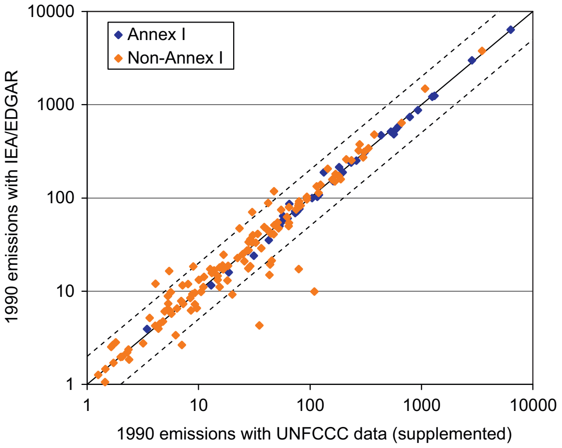

Fig. 8. Emission estimates for 1990 for different countries (Mt CO_2-eq, logarithmic scale) based on UN-FCCC (*X*-axis) or IEA/EDGAR (*Y*-axis). The dashed lines indicate points where one estimate is twice the magnitude of the other estimate.

The different datasets can exhibit considerable differences in their estimates. Fig. 8 presents emissions in the EVOC database with UN-FCCC and IEA/EDGAR-based data. Large deviations can be seen from the diagonal line, representing equal estimates between the sources, and for many individual countries the difference is over 100%, indicated by the dashed lines in the figure. As the effort sharing is based on these emission estimates, through sectoral projections in Triptych and emissions per capita in Multistage, the accuracy of emission estimates is material. Using different historical emission estimates might imply differences of several tens of percentage points on the allowances a country receives.

4.4. Assumptions behind the effort sharing

Obviously, effort sharing with the Triptych and Multistage approaches is dependent on the underlying assumption and parameter choices which define the allocation of emission allowances. Therefore a risk exists that if the parameters are inaccurate, the effort sharing can end up being erroneous.

This is especially problematic for the Triptych approach, as it is the more complicated one from the approaches assessed in this paper. The effort sharing with Triptych is based on assumptions on feasible mitigation potentials in each sector, which are in turn very uncertain in the very long term as noted in Section 3.1. Then, if the actual potentials in the future differ from those assumed, the emission allocation favors the countries, for which the mitigation potential has been underestimated.

During the study a notable difference in sectoral mitigation potential estimates—especially in agriculture—between EVOC and TIAM was noted, which prompted to a recalibration of EVOC to match the results from TIAM. Fig. 9 presents the results from EVOC for Triptych 550 ppm effort sharing in 2020 and 2050 before and after the recalibration. This recalibration had a large effect especially for certain countries. As an example, Australia received 66% more allowances in 2050 after the recalibration, reducing its economic burden substantially. A difference of this magnitude highlights clearly the importance of assumptions used in the effort sharing process.

5. Conclusions and discussion

This study has analyzed global effort sharing of climate change mitigation with Triptych and Multistage effort sharing rules and two mitigation scenarios aiming at -10% and -50% reductions from 1990 levels by 2050, leading to concentrations of 550 ppm CO_2-eq and 485 ppm CO_2-eq by 2100, respectively. Being simple and transparent, the EVOC tool of Ecofys GmbH was used for calculating Triptych and Multistage emission allocations, while and ETSAP-TIAM, a sophisticated but complex global energy system model of the TIMES family was used for creating the scenarios.

The available mitigation measures and their costs is crucial also for effort sharing, as the source distribution of emissions varies between countries and therefore regional mitigation potentials depend on the technological assumptions and resource estimates. Due to this, an explicit description of reduction measures undertaken in the scenarios was given. Most of the reductions were realized in electricity generation and industry. In other sectors numerous measures, however, mostly with limited potentials, were taken.

In the case of ambitious emission reductions, more unconventional measures have to be used. As many measures in transportation and agriculture were deemed to have limited mitigation potentials, reduced demand or substitution with lower

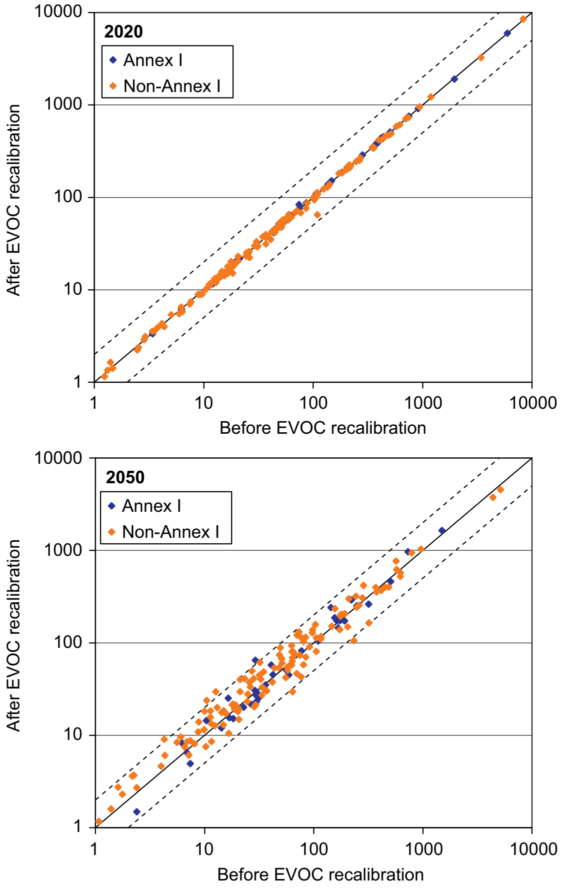

Fig. 9. Emission allocations (Mt CO_2-eq, logarithmic scale) with Triptych 550 ppm effort sharing before (*X*-axis) and after (*Y*-axis) EVOC recalibration in 2020 (top) and 2050 (bottom). The dashed lines indicate points where one estimate is twice the magnitude of the other estimate.

emitting alternatives was the only alternative for sufficient emission reductions. This was particularly the case with aviation, cattle and rice. The use of unconventional measures, however, also increases the uncertainty on mitigation costs and future allowance prices, rendering equitable effort sharing a challenging task.

The mitigation costs in the scenarios were relatively high compared to previous studies, reaching even 4–5% of global GDP with the 485 ppm target, by 2050. Also, the price of allowances was high, reaching even 1000$\$_{2000}$/t in 2050 with the 485 ppm target but being very dependent on the baseline scenario used. After accounting for differing reduction targets, the cost differences were identified to arise from less optimistic non-CO_2 mitigation potentials and the exclusion of afforestation options in this study. Although deforestation and afforestation are problematic for effort sharing due to the large uncertainties involved, they might be critical for reaching deep mitigation targets cost-efficiently.

Triptych and Multistage both allocate moderate reductions for Annex I and allow non-Annex I emissions to increase from 2000 levels by 2020. In 2050, Annex I faces very stringent targets around 80% from 2000 emissions, and only for the least developed non-Annex I regions the allowances exceeded their 2000 emissions. This is reflected also in mitigation costs with Annex I having positive costs and most or some non-Annex I regions having net gains due to allowance sales. Emission trading proved to be the most important single factor in the costs for most regions. The most extreme case was India in 2050, which was able to gain from 1% to over 10% of its baseline GDP from allowance sales.

A comparison between the economic burden the regions face and their abilities, by using GDP (PPP) per capita as a wealth measure, showed that both Triptych and Multistage produce equitable costs, although the balance of favoring the least developed and penalizing the most developed is obviously debatable. Overall, Triptych exhibited more moderate costs than Multistage for Annex I while still providing gains for non-Annex I, and might be thus be acceptable for both Annex I and non-Annex I. Triptych also exhibited higher coherence, i.e. the effort of individual regions varied less from the average. This highlights that an approach not taking into account the sectoral distribution of emissions and differing mitigation potentials can not adequately produce an equitable outcome. The coherence of Triptych did, however, degrade with the more stringent target, as the allocations are then mostly based on per-capita-based targets also with the Triptych approach.

Even if the effort can be shared equitably in theory, it might prove hard in practice. The future price of allowances varied considerably depending on the baseline, and studies with different models, and thus different assumptions, give even a wider range of possible price projections. A remark was also made on the data and assumptions behind effort sharing. Emissions estimates for especially non-Annex I are very uncertain, which makes effort sharing based on historical or projected emissions problematic. Also, if the effort sharing method specifies mitigation potentials in some form, as in the Triptych approach, these estimates have to be reliable, as was indicated by the Triptych recalibration experiment.

Given these uncertainties, fixing allowance allocations in the very long term might not be reasonable. As the mitigation costs cannot be accurately observed in reality, correcting distortions later on by reassessing the allocations would be challenging.

The analysis presented here has still some limitations. The partial equilibrium approach, while providing a detailed picture on the energy system, does not include any feedback effects from the rest of the economy. Effort sharing, especially in the extreme cases, might involve large wealth redistributions through allowance markets, affecting affluence levels and energy demand. Also, a high price of emissions is likely to induce structural change in the economy. Should the demand and production structures adjust to the cost of carbon, the mitigation costs then would be lower than reported here. With the TIAM model, the only possible adjustment is reduced demand, i.e. welfare loss, instead of e.g. demand substitution.

What was also not considered here, is the avoided damage costs from climate change through mitigation. Potential damage costs and adaptation capabilities vary largely between countries, and therefore should be also included in the analysis. This would, however, make the results unreliable due to the large uncertainties. Linking effort sharing to the funding of adaptation and technology transfer would still be reasonable, as all deal with transferring resources to the least developed and most vulnerable regions.

Last, the smooth operation of allowance markets and full participation of the parties is essential for cost-effectiveness.

Cases with transaction costs and limited participation both resulted with a doubling of global mitigation costs in 2020. Ensuring efficiency is, however, an issue of market design, but it might affect also effort sharing as the marginal costs are not necessarily equalized globally with inefficient markets.

Despite all these challenges, effort sharing is a necessity for the post-2012 climate policy. The negative costs for non-Annex I from the Triptych and Multistage, especially in the medium term, might provide a sufficient incentive for developing countries to accept binding targets. However, the gains are a result of wealth transfer from Annex I countries through allowance trading, the amount of which must be acceptable for Annex I countries. In this respect Triptych might provide a more balanced outcome of the two regimes assessed. It is yet good to bear in mind that the effort sharing will ultimately be a result of political negotiations. As said, there is no definitive answer to the equitable balance between costs and gains of different parties, but a quantified assessment of possible outcomes might aid the process considerably.

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Appendix A. Detailed results from effort sharing

Main quantitative results from effort sharing in the mitigation scenarios for each region is provided in Tables 2–5.

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version at 10.1016/j.enpol.2009.11.055.

Table 2
Main outcomes of effort sharing with the 485 ppm-eq target in 2020—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	15 000–16 000	7.9–8.4	6.6–7	5.1–5.7	21–48	4.4–4.9	32–66
W.Eur	14 000–15 000	4.7–5.1	3.7–4.2	2.9–3.2	14–33	3–3.3	13–32
FSU	3000–4100	3.4–3.9	2.8–3	2.3–2.5	5.8–17.4	2.6–2.8	1.2–15.0
E.Eur	1800–2600	0.88–0.99	0.72–0.79	0.73–0.78	0.4–2.3	0.89–0.95	−2.8−−0.6
Japan	4000–4500	1.3–1.4	1.1–1.1	0.86–0.94	2.4–4.5	0.89–1	0.7–3.6
Canada	1200–1400	0.75–0.79	0.59–0.64	0.37–0.41	4.4–8.2	0.36–0.4	4.5–8.5
Aus&NZ	820–920	0.74–0.74	0.57–0.62	0.52–0.56	2.2–3.7	0.34–0.38	5.0–8.4
China	12 000–17 000	6.6–7.3	5–5.4	6.8–7.7	−36−−11	6.2–7.2	−22−−2.7
L.Am	5300–6000	3–3.2	2.7–2.9	2.9–3.3	−4.4–9.7	2.3–2.8	2.2–19.8
Oth. Asia	5800–8100	3.2–3.9	2.8–3.3	3.4–3.7	−12.0−−7.4	3.6–3.9	−16−−11
Africa	4000–4800	3.2–3.4	2.8–2.9	2.9–3.2	−2.8–3.7	3–3.6	−12.0–1.6
India	5500–8500	2.9–3.6	2.2–2.5	2.7–3.1	−7.4−−3.1	3.8–4.5	−44−−19
M.East	3400–4000	2.8–3.2	2.5–2.8	2.3–2.5	12–58	2–2.3	14–65
Mexico	1700–1900	0.73–0.76	0.64–0.67	0.73–0.82	−1.4–0.8	0.57–0.7	0.4–3.3
S.Korea	1500–2100	0.74–1	0.59–0.75	0.56–0.62	−0.5–1.7	0.45–0.53	2.2–3.7

All values are on an annual basis, monetary values in USD2000.

Table 3
Main outcomes of effort sharing with the 550 ppm-eq target in 2020—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	15 000–16 000	7.9–8.4	6.6–7	5.1–5.7	13–44	4.2–4.8	19–59
W.Eur	14 000–15 000	4.7–5.1	3.7–4.2	2.9–3.2	7–30	3–3.4	6–29
FSU	3000–4100	3.4–3.9	2.8–3	2.3–2.5	2.9–10.1	2.3–2.5	3.8–16.5
E.Eur	1800–2600	0.88–0.99	0.72–0.79	0.73–0.78	−0.5–1.1	0.78–0.83	−0.5–2.3
Japan	4000–4500	1.3–1.4	1.1–1.1	0.86–0.94	1.7–5.3	0.89–1	1.1–4.5
Canada	1200–1400	0.75–0.79	0.59–0.64	0.37–0.41	2.3–6.5	0.35–0.39	2.5–7.1
Aus&NZ	820–920	0.74–0.74	0.57–0.62	0.52–0.56	1.0–3.1	0.41–0.47	1.9–5.4
China	12 000–17 000	6.6–7.3	5–5.4	6.8–7.7	−29−−9	6.8–7.9	−21−−6.2
L.Am	5300–6000	3–3.2	2.7–2.9	2.9–3.3	−5.2−−0.9	3–3.7	−5.6–0.2
Oth. Asia	5800–8100	3.2–3.9	2.8–3.3	3.4–3.7	−15.6−−7.3	4.1–4.6	−22−−9
Africa	4000–4800	3.2–3.4	2.8–2.9	2.9–3.2	−5.4−−0.5	3.2–4	−12.3−−0.1
India	5500–8500	2.9–3.6	2.2–2.5	2.7–3.1	−11.7−−3.8	3.8–4.5	−30−−9
M.East	3400–4000	2.8–3.2	2.5–2.8	2.3–2.5	9–35	2.1–2.5	8–36
Mexico	1700–1900	0.73–0.76	0.64–0.67	0.73–0.82	−1.5−−0.7	0.72–0.88	−1.5−−0.2
S.Korea	1500–2100	0.74–1	0.59–0.75	0.56–0.62	−0.9–1.2	0.63–0.73	−1.0–0.6

All values are on an annual basis, monetary values in USD2000.

Table 4
Main outcomes of effort sharing with the 485 ppm-eq target in 2050—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2-eq	Emissions Gt CO_2-eq	Triptych alloc. Gt CO_2-eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2-eq	Multist. cost Bln. USD
USA	22 000–30 000	8.8–11	2–2.4	0.56–0.63	1658–3052	0.39–0.56	1788–3094
W.Eur	18 000–27 000	5.2–6.4	1.1–1.4	0.58–0.66	787–1417	0.41–0.6	897–1450
FSU	6600–14 000	4.8–7.7	0.56–1.2	0.45–0.56	679–1819	0.34–0.44	774–1931
E.Eur	3100–6700	1.1–1.7	0.18–0.23	0.16–0.19	119–279	0.13–0.17	141–301
Japan	4900–6800	1.3–1.5	0.18–0.29	0.16–0.19	172–271	0.13–0.19	196–262
Canada	1800–2700	0.83–1.1	0.073–0.25	0.065–0.073	173–301	0.042–0.06	190–312
Aus&NZ	1100–1600	0.76–0.88	0.11–0.2	0.084–0.09	147–217	0.027–0.037	184–267
China	22 000–47 000	7.3–11	1.7–2.3	2.3–2.7	320–1005	1.6–1.9	822–1695
L.Am	12 000–18 000	4.8–6.5	1.3–1.6	1.3–1.6	672–1505	0.85–0.94	1057–1887
Oth. Asia	13 000–28 000	4.9–8.7	1.5–2.3	2.3–2.4	56–1107	2.4–2.7	−170–771
Africa	12 000–22 000	6.4–8.5	2–2.3	2.9–3.3	−260–453	3.2–4	−545–25
India	14 000–38 000	4.5–8.6	1.1–1.3	2.3–2.6	−455–−208	3.2–4.8	−2767–−778
M.East	8500–15 000	5.4–8.8	1.1–1.6	0.92–1.1	892–2349	0.54–0.76	1197–2696
Mexico	3900–6200	1.2–1.6	0.29–0.34	0.33–0.35	136–315	0.18–0.2	236–453
S.Korea	2800–5900	0.95–2.1	0.11–0.32	0.11–0.13	153–524	0.06–0.069	176–587

All values are on an annual basis, monetary values in USD2000.

Table 5
Main outcomes of effort sharing with the 550 ppm-eq target in 2050—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2-eq	Emissions Gt CO_2-eq	Triptych alloc. Gt CO_2-eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2-eq	Multist. cost Bln. USD
USA	22 000–30 000	8.8–11	3.4–3.7	1.2–1.4	595–1721	0.9–1.1	699–1769
W.Eur	18 000–27 000	5.2–6.4	1.8–2	1.1–1.2	281–780	1.1–1.2	305–719
FSU	6600–14 000	4.8–7.7	1.8–2.1	0.87–1.1	278–1009	0.7–0.76	335–1179
E.Eur	3100–6700	1.1–1.7	0.35–0.38	0.37–0.4	26–107	0.26–0.3	47–161
Japan	4900–6800	1.3–1.5	0.37–0.48	0.29–0.31	70–154	0.32–0.37	68–113
Canada	1800–2700	0.83–1.1	0.36–0.39	0.15–0.19	61–153	0.1–0.11	79–175
Aus&NZ	1100–1600	0.76–0.88	0.25–0.38	0.17–0.21	44–118	0.091–0.1	67–156
China	22 000–47 000	7.3–11	3.1–3.7	4.5–5	−180–−44	3.7–4.8	−66–514
L.Am	12 000–18 000	4.8–6.5	2.5–3	2.3–3	110–708	2–2.3	245–887
Oth. Asia	13 000–28 000	4.9–8.7	2.6–3.4	3.7–4	−108–260	4–4.3	−212–73
Africa	12 000–22 000	6.4–8.5	3.4–3.5	4–4.8	−215–144	5–5.6	−655–−201
India	14 000–38 000	4.5–8.6	1.9–2.2	3.7–4.6	−649–−213	5.2–6.2	−1278–−524
M.East	8500–15 000	5.4–8.8	2.3–2.9	1.6–2.1	445–1426	1.1–1.4	572–1761
Mexico	3900–6200	1.2–1.6	0.49–0.63	0.65–0.71	22–129	0.47–0.55	54–223
S.Korea	2800–5900	0.95–2.1	0.35–0.54	0.26–0.4	49–241	0.17–0.2	60–348

All values are on an annual basis, monetary values in USD2000.

References

Böhringer, C., Welsch, H., 2004. Contraction and convergence of carbon emissions: an intertemporal multi-region cge analysis. Journal of Policy Modeling 26 (1), 21–39 doi:10.1016/j.polmod.2003.11.004.

DeAngelo, B.J., de la Chesnaye, F., Beach, R.H., Sommer, A., Murray, B.C., 2006. Methane and nitrous oxide mitigation in agriculture. The Energy Journal 27, 89–108.

den Elzen, M., Lucas, P., van Vuuren, D., 2005. Abatement costs of post-kyoto climate regimes. Energy Policy 33 (16), 2138–2151.

den Elzen, M.G., Berk, M., Lucas, P., Criqui, P., Kitous, A., 2006. Multi-stage: a rule-based evolution of future commitments under the climate change convention. International Environmental Agreements: Politics, Law and Economics 6 (1), 1–28.

den Elzen, M.G., Höhne, N., Brouns, B. Winkler, H., Ott, H.E., 2007. Differentiation of countries' future commitments in a post-2012 climate regime: an assessment of the south–north dialogue proposal. Environmental Science & Policy 10 (3), 185–203, doi:10.1016/j.envsci.2006.10.009.

den Elzen, M., Höhne, N., Moltmann, S., 2008a. The triptych approach revisited: a staged sectoral approach for climate mitigation. Energy Policy 36 (3), 1107–1124 doi:10.1016/j.enpol.2007.11.026.

den Elzen, M.G.J., Lucas, P.L., Van Vuuren, D.P., 2008b. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations. Climatic Change 90 (3), 243–268.

Edmonds, J., Clarke, L., Lurz, J., Wise, M., 2008. Stabilizing CO_2 concentrations with incomplete international cooperation. Climate Policy 8 (4), 355–376 doi:10.3763/cpol.2007.0469.

FAO, 2009. FAOSTAT database. URL: faostat.fao.org.

Fisher, B., Nakicenovic, N., Alfsen, K., et al., 2007. Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Groenenberg, H., Phylipsen, D., Blok, K., 2001. Differentiating commitments world wide: global differentiation of GHG emissions reductions based on the triptych approach—a preliminary assessment. Energy Policy 29 (12), 1007–1030 doi:10.1016/S0301-4215(01)00027-1.

Höhne, N., Phylipsen, D., Moltmann, S., 2006. Factors underpinning future action. Technical Report, Ecofys GmbH.

IPCC, 2000. Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In: Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K. (Eds). Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.

Loulou, R., 2008. ETSAP-TIAM: the TIMES integrated assessment model part II: mathematical formulation. Computational Management Science 5 (1–2), 41–66.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model part I: model structure. Computational Management Science 5 (1–2), 7–40.

Loulou, R., Remme, U., Kanudia, A., Lehtilä, A., Goldstein, G., 2005a. Documentation for the times model. Technical Report DM 70046/ICC03080, IEA Energy Technology Systems Ananlysis Programme (ETSAP) 〈http://www.etsap.org/documentation.asp〉.

Loulou, R., Waaub, J.-P., Zaccour, G., 2005b. Energy and Environment. Springer, US (Chapter 11).

Lucas, P.L., van Vuuren, D.P., Olivier, J.G., den Elzen, M.G., 2007. Long-term reduction potential of non-CO_2 greenhouse gases. Environmental Science & Policy 10 (2), 85–103 doi:10.1016/j.envsci.2006.10.007.

Macintosh, A., Wallace, L., 2009. International aviation emissions to 2025: can emissions be stabilised without restricting demand? Energy Policy 37 (1), 264–273 doi:10.1016/j.enpol.2008.08.029.

Manne, A.S., Stephan, G., 2005. Global climate change and the equity-efficiency puzzle. Energy 30 (14), 2525–2536.

Miketa, A., Schrattenholzer, L., 2006. Equity implications of two burden-sharing rules for stabilizing greenhouse-gas concentrations. Energy Policy 34 (7), 877–891.

Persson, T.A., Azar, C., Lindgren, K., 2006. From production-based to consumption-based national emission inventories. Energy Policy 34 (14), 1889–1899.

Peterson, S., Klepper, G., 2007. Distribution matters—taxes vs. emissions trading in post kyoto climate regimes. Kiel Working Paper 1380, Kiel Institute for the World Economy.

Phylipsen, D., Höhne, N., Janzic, R., 2004. Implementing triptych 6.0—technical report. Technical Report.

Phylipsen, G.J.M., Bode, J.W., Blok, K., Merkus, H., Metz, B., 1998. A triptych sectoral approach to burden differentiation; ghg emissions in the European bubble. Energy Policy 26 (12), 929–943 doi:10.1016/S03014215(98)00036-6.

Rao, S., Riahi, K., 2006. The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. The Energy Journal 27, 177–200.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74 (7), 887–935.

Ringius, L., Torvanger, A., Holtsmark, B., 1998. Can multi-criteria rules fairly distribute climate burdens? OECD results from three burden sharing rules. Energy Policy 26 (10), 777–793.

Russ, P., Ciscar, J. C., Szabo, L., 2005. Analysis of post-2012 climate policy scenarios with limited participation. Technical Report.

Syri, S., Lehtila, A., Ekholm, T., Savolainen, I., Holttinen, H., Peltola, E., 2008. Global energy and emissions scenarios for effective climate change mitigation—deterministic and stochastic scenarios with the TIAM model. International Journal of Greenhouse Gas Control 2 (2), 274–285.

Vaillancourt, K., Waaub, J., 2004. Equity in international greenhouse gases abatement scenarios: a multicriteria approach. European Journal of Operational Research 153 (2), 489–505.

van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B.J., van Ruijven, B., Wonink, S., van Houdt, R., 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change 81 (2), 119–159 doi:10.1007/s10584-006-9172-9.

ARTICLE IV

The effect of financial constraints on energy-climate scenarios

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The effect of financial constraints on energy-climate scenarios

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HIGHLIGHTS

- Climate and electrification targets increase the capital required for investments.
- Required low-cost capital might not be available in developing countries.
- Paper presents capital-constrained scenarios on electricity generation in Africa.
- The cost of capital affects technology choice and emission levels considerably.
- Climate policy effectiveness is dependent on the availability of low-cost capital.

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ABSTRACT

In this paper, we discuss the implications of financing constraints for future energy and climate scenarios. Aspirations to improve energy access and electrification rates in developing countries, while simultaneously reducing greenhouse gas emissions, can be seriously hindered by the availability of low-cost capital for the necessary investments. We first provide a brief description of the theoretical foundations for financing constraints in the energy sector. Then, using a broad range of alternate assumptions we introduce capital supply curves to an energy system model for Sub-Saharan Africa, with a specific focus on the power sector. Our results portray the effect of capital cost on technology selection in electricity generation, specifically how limited capital supply decreases investments to capital-intensive zero-emission technologies. As a direct consequence, the emission price required to meet given emission targets is considerably increased when compared to case that disregards the capital constraints. Finally, we discuss possible policy instruments for resolving the constraints.

1. Introduction

Affordable, accessible and reliable energy supply is essential for economic growth and poverty reduction in developing countries. In addition, because a global approach is required to mitigate climate change, investment into renewable energy sources is necessary also in developing countries, thus adding to the investment need. Yet, necessary capital for the investments might not be available at reasonable cost, and the situation can be particularly dire in Sub-Saharan Africa. In this paper we aim to analyse whether and how financial constraints[1] in the power sector would affect energy-climate scenarios that aim at improved energy access and greenhouse gas emission reductions in Sub-Saharan Africa.

Financial constraints are a pertinent feature of the energy industry. Energy projects are typically capital-intensive, large, lumpy, and with long pay-back periods and their financing is a delicate task. If not enough capital is mobilized toward these projects, under-investment will lead to adverse consequences such as low supply capacity, poor access, unreliable supply, sub-optimal technology portfolio, high energy prices and adverse environmental effects. Under-investment can exist at the entire energy sector level or be related to particular sub-sectors or technologies. As an example of the latter case, certain high-profit low-risk sectors (such as upstream oil and gas) may attract a large amount of funds, while other sectors (such as electricity generation) may face under-investment. This creates an imbalance

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[1] "Financial constraints" is a standard technical expression in the finance literature. It refers to the situation in which an agent has limitations in accessing "low cost" funds. However, financial constraints does not necessarily imply a hard constraint on the total supply of capital as the agent can move to another step and obtain further (potentially highly expensive) funds by paying extra premium.

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between upstream and downstream supply capacities. Due to this, financial constraints should be considered separately for sectors that are internally homogeneous, and this paper focuses primarily on the electricity generation sector.

In an ideal environment in which markets are complete[2] and competitive, all positive and negative externalities are priced,[3] and no information asymmetry exists,[4] investments will be at a socially optimal level. However, various frictions in the energy sector, government regulations, and financial markets may lead to under-investment—the level of investment being lower than the economically efficient level. Thus, addressing this problem is an important public policy issue both at developed and developing regions. In this paper, we focus on these frictions and elaborate their causes and effects both conceptually and quantitatively.

The adverse impact of financing constraints on energy supply, as well as on the demand side, has been recognized and discussed by academicians and policy institutions. Examples include IEA (2003), Fritz-Morgenthal et al. (2009), and Mukherjee and Pratap (2011). Most of them discuss the immediate impacts of a negative capital supply shock on short-term energy goals. However, only few studies have attempted to quantify implications of financing limitations at a national or regional level for a long horizon scenario. Awerbuch (1993) notices this effect and mentions that in the energy planning systems, considering the effect of risk premium may change the optimal energy portfolio.

In order to fill this gap and to portray the specific effect of financial constraints on electricity generation and emissions, we introduce capital supply curves into a linear cost-minimizing energy scenario model. The model is calibrated to energy scenarios for Sub-Saharan Africa reported in the Global Energy Assessment (GEA) (Riahi et al., 2012), assessing pathways to reduce greenhouse gas emissions and to improve energy access in developing countries between 2020 and 2050. Then, scenarios with capital constraints on electricity investments are used to explore how the cost of capital affects technology selection, the monetary level of investments and greenhouse gas emissions in the scenarios. As it is challenging to estimate how the investment capacity will develop during the coming decades, we calculate capital-constrained energy scenarios for Sub-Saharan Africa with multiple capital supply curves, with parameter ranges estimated from historical performance of the energy investment in the region. Our final consideration deals with the relationship between capital costs and emission pricing necessary to meet emission targets, and how global climate policy might be employed to alleviate the capital scarcity problem.

The paper is organized as follows. First, we describe the basic concepts of investment in the energy sector. The following chapter focuses on the context of our study, discusses the investment scenarios for Sub-Saharan Africa and the capacity of the region to finance energy projects. Section four introduces the modelling strategy and our approach to include financing constraints in the energy planning system. Finally, we report the results from running the model and discuss possible policy options.

2. Energy financing

In this Section we introduce briefly the theoretical foundations of investment and financial constraints in the energy sector. The goal is to elaborate the multi-faceted nature of investment problems and provide a clear and consistent treatment to be used in energy models. Our consideration of financial constraints focuses primarily on the supply side of finance and the costs of financing, although the capacity of the energy sector to absorb the financing and carry out the associated physical investment can also be constraining factors.

2.1. Framework for investment

Energy firms can finance their projects through three major channels: internal cash-flow, equity markets, and debt markets. Internal cash-flow is a function of market structure as well as government regulations regarding input and output markets. Equity and debt are mainly channelled through financial markets and institutions, including commercial banks, stock market, investment banks, private equity investors and large institutional investors such as pension funds.

A higher level of financial development implies that these institutions are more efficient, innovative, and better capable of serving the financing needs of energy projects (e.g. Levine, 1997; Love, 2003). Energy projects in countries with lower level of financial development may face further challenges and barriers in accessing external financing. This would limit the ability of public and private sector to implement socially beneficial projects.[5]

Under-investment can result from certain frictions. In an ideal world, the social planner will choose the optimal path of investment in each sector (including the energy sector) in a way that the marginal benefits of each unit of capital becomes equal to the marginal costs of investment.[6] In this framework, under-investment does not exist because the marginal utility of consumption (i.e. output prices) as well as saving rates will adjust to supply an optimal level of capital for the most socially beneficial sectors. Also, at the corporate level, the Modigliani and Miller (1958) theorem postulates that financial structure (i.e. the choice of debt versus equity) should not matter since debt and equity will be perfect substitutes in a perfect market.

In reality, however, various frictions can prevent socially-optimal resource allocation, both at aggregate (macro) and project (micro) levels. At the macro level, factors such as poor property rights and weak contract enforcement (La Porta et al., 1998; Clague et al., 1999), improper regulations of financial markets (Galindo et al., 2007), inefficient financial intermediary sector (Bencivenga and Smith, 1991), high inflation and macroeconomic instability (Servén, 2003), and tax policies (Bernheim, 2002) can lead to low aggregate saving rates and low capital formation.

On the other hand, project-level financing constraints can still exist even if the aggregate national savings and capital formation are high. Underlying reasons for this include information asymmetries between financiers and entrepreneurs (Stiglitz and Weiss, 1981; Myers and

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[2] Market completeness means that there are traded contracts for every possible contingency in future and there is a price for them. This allows having a unique price for any risky production technology. Obviously, reality is far from this assumption.

[3] Externalities exist when the negative or positive effects of an activity affects other agents in the economy without being reflected in its private price. As an example of positive externality, one can refer to climate effects of renewable technologies. If positive externalities are not included in the price, agents will under-invest in that technology.

[4] There are two main types of informational asymmetries in the financing practice. Adverse-selection refers to a situation in which a financier cannot distinguish between high quality and low quality investment projects. Moral-hazard happens when the entrepreneurs who has received some external financing behaves in a way to maximize her benefits and not necessarily the benefits of the financier. In aggregate level, both types results in lower provision of funds to investment projects.

[5] Unless there is a substantial non-priced negative externality associated with firms' activities (e.g. damaging environment), implementing a positive-NPV project by a commercial corporation will improve social welfare.

[6] Marginal cost of investment may include the cost of capital goods, rental price of capital, adjustment costs, fixed cost of installing new capital, and finally the cost of forgone waiting options.

Table 1
Summary of different types of under-investment.

Type of under-investment	Underlying reasons	Solutions
Low aggreagate investment	Low saving rates, poor financial sector, macroeconomic uncertainty	Interest rate policies, improving property rights, promoting FDI
Low investment in the energy sector	Inefficient energy regulations, higher transaction costs of energy investment	Higher investment incentives
Low investment in particular energy technologies	High technology-specific risk premium	Specialized finance

Majluf (1984)) or incentive problems inherent in project selection (Jensen and Meckling, 1976). Moreover, government regulations on product markets (e.g. output price controls) could lower returns to capital in certain sectors and create barriers for capital flow to those sectors. As a result, funds are not invested in the socially most beneficial projects. Table 1 summarizes different forms of under-investment.

2.2. The cost of capital

Standard finance theory suggests that due to the risk-aversion of agents, investors take systematic (non-diversifiable) risks only if the risk-taking is rewarded with expected returns that are higher than from lower-risk investments. To avoid the misuse of the concept, enough attention should be given to the definition of risk in this context. The risks which come with a reward should be the systematic one, meaning that investors are not be able to eliminate them using diversification or hedging.[7] The Capital Asset Pricing Model (CAPM) (Lintner, 1965), an essential model in modern finance, suggests that investors receive extra premium only to the extent that their return is co-moving with the market return.[8] This model implies that if firms issue equity in order to finance their projects, the expected return to pay to buyers (financiers) should be proportional to the co-movement of firm's cash-flow with the market returns. As a result, firms which produce goods and services the demand of which moves strongly with business cycles (high beta firms) have to sell their shares at lower prices compared to those firms which produce counter-cyclical products and services.

A general structure for the cost of capital comprises the following elements.

1) Risk-free rate: This is the base rate that investors demand for accepting any investment project.
2) Market price risk: When projects are risky, investors demand a higher compensation to bear the risk. The market price of risk is the extra premium to pay for every unit of systematic risk, and measured with the firm's beta: the co-movement between firm's pay-off and the market returns.
3) In addition, firms may have to pay extra transaction costs (like brokerage fee or bank fee) to issue securities or receive a loan. If a country has a more active financial market, these elements would be lower in general. Hail and Leuz (2006) find that firms in countries with more extensive security regulations and better law enforcement pay a lower cost of capital. Estache and Pinglo (2004) find that the cost of capital has a negative relationship with the economic development. Their estimations, using the data for the cost of equity and debt for a large number of infrastructure projects, suggest that these projects has the highest cost of capital in Africa and Middle-East (14%) and the lowest in South Asia and Pacific (8.5%).[9]

Theoretically, estimating the cost of capital for a given subsector should be straightforward. The standard procedure is to regress a company's stock returns on the market returns to produce the beta of the company as a measure for the cost of capital. For mature industries, this is usually done using stock market data. Unfortunately, risk and return data for a sufficient empirical estimation are not readily available for most of the new technologies, such as renewable energy technologies; or the energy sector of least developing countries.

Despite of its theoretical attractiveness, CAPM shows a poor performance in various empirical tests, implying the possibility of other “priced” risk factors in addition to the market return risk. Fama-French (1993) among others, have suggested candidates for these missing risk factors. In the Fama-French model, the difference between the returns of High versus Low book-to-market firms (aka HML factor) and Small versus Big firms (aka SMB factor) are extra factors which should be considered in a cost of capital estimation.

Moreover, using stock market data for this purpose is not free of its own problems. A financial modeller is interested in the *expected* returns. However, it is not possible to observe the ex-ante expectations and one needs to use rational expectations hypothesis and ex-post data to estimate the ex-ante values. Realized stock returns (ex-post data) contain information on the expected returns (ex-ante measures) as well as realized shocks to the cash-flow of the firm.

2.3. Financing frictions

Throughout this study, we take as a given that some financing frictions exist in the economy and highlight two distinct channels of that phenomenon. The first channel is limitations of the aggregate investment in the entire energy sector. This effect, once binding, shifts the energy portfolio toward less capital intensive technologies. The second effect comes through differences in risk premium among various energy technologies. There are several mechanisms creating such difference.

First, the correlation between pay-offs and business cycles varies between technologies, affecting the systematic risk of technologies. In electricity generation the correlation is determined by how the difference in input and output prices varies between booms and recessions. For fuel-based technologies (e.g. gas and coal) both factors correlate, whereas for renewables and nuclear – for which fuel plays minor role in generation costs – the correlation arises from the electricity price variability only. The correlation in pay-offs might generally thus be higher for renewables, which would associate with a higher CAPM type risk premium.

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[7] In the literature of energy finance, sometimes authors do not differentiate between systematic and idiosyncratic risks and point out to all types of risks (such as technical failure) as source of risk premium, which is not always correct.

[8] CAPM model assumes that by investing in large number of uncorrelated assets, one can eliminate the asset-specific risks. Therefore, in equilibrium no extra premium is required for those risks.

[9] For comparison, Cambini and Rondi (2010) reported the cost of capital for utilities in five European countries to average at 7%.

Second, there is a difference between large-scale and long-term investment projects and small-scale and short-term projects. Acemoglu and Zibotti (1997) suggest that because of this effect, investors will invest on safer projects with lower return. They show when the economy grows, further investment opportunities emerge and agents are willing to invest a higher proportion of their savings into riskier projects. An extra risk premium should be associated to large-scale projects to capture some of market incompleteness effects mentioned before such as the limited space for diversification or uninsured risks. This issue is more pronounced in developing countries that lack a liquid, large, and efficient financial market. However, large-scale and pioneering projects may face financing difficulties even in the developed countries, and have to pay an extra risk premium to attract investors.

Finally, investment in emerging and non-conventional technologies, as well as in projects which may face regulatory challenges (e.g. nuclear power plants), is more risky due to the probability of failure or stoppage and hence losing any expected future cash-flow. Adding a risk-premium to the required rate of return in this type of projects ensures that investors will have enough incentive to enter to the project.

To attract domestic private investment the energy sector has to compete with other sectors of the economy under consideration. International investors can be more specialized, and the competition is more between energy sectors in different regions. Hence the international funds for a country's power sector might be drained by the power sector in another country that has a more favourable investment climate. Government policies are quite influential for this source of funding. For example, Blackman and Wu (1999) show that in the case of China, limiting regulations in the 1990s channeled foreign direct investments (FDI) mainly toward small-scale projects. This may limit the overall impact of FDI despite a large quantity of total investment.

2.4. Implications of cost of capital on energy investment

The cost of capital has implications on several levels. On the aggregate level of the whole economy, capital acts as a factor of production and its cost affects the equilibrium level of energy supply and demand. On the project level, the cost of capital also affects the balance between capital and running costs, and therefore affects the choice of production technology. This has important consequences for greenhouse gas emission control, as emission reductions are pursued mainly through shifts to cleaner but more capital intensive technologies.

As an illustration, we approach the technology selection problem first though a simple cost-minimization analysis. In order to supply a unit of electricity (neglecting the system integration costs), the producer has several technology choices with differing characteristics. We assume that the price of supplied electricity does not depend on the selected technology (i.e. we assume no market power for energy firms), so that the profits of a price-taking producer are maximized with a technology that minimizes the levelized production costs. Using the technology characteristics and fuel prices for Sub-Saharan Africa from the Global Energy Assessment (GEA) (Riahi et al., 2012) for year 2020, Fig. 1 portrays the cost-minimizing technologies for different capital cost and emission price levels. The obvious shift from more to less capital intensive technologies as the discount rate is increased is clearly presented in the figure. In addition, an interesting feature is the steep slope between the cost-optimality regions of the renewable and fossil technologies. An implication from this is that with higher costs of capital, the price of emissions that is required to make renewables the optimal technology is increased significantly.

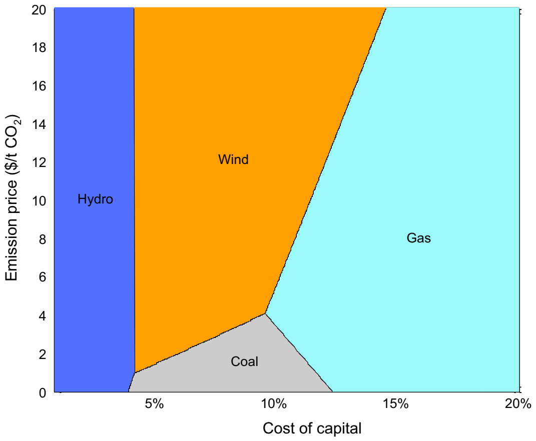

Fig. 1. A diagram that shows the cost-minimizing technology with different levels of capital costs and emission prices. The underlying technology and price assumptions are for the year 2020 from the illustrative GEA Mix scenario (Riahi et al., 2012).

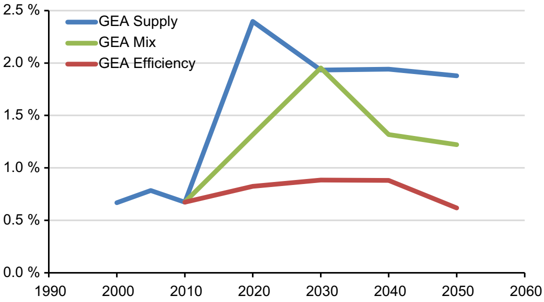

Fig. 2. Electricity investments relative to GDP in Sub-Saharan Africa in three illustrative GEA scenarios (Riahi et al., 2012).

3. Energy investment in Sub-Saharan Africa

3.1. Future investment needs

Our analysis is based on the scenarios reported in GEA (Riahi et al., 2012). Fig. 2 presents the monetary amount of electricity investments relative to the projected GDP of Sub-Saharan Africa in three illustrative GEA scenarios aiming at a 450 ppm CO_2-eq greenhouse gas concentration target. Although the range of investment levels is wide – resulting from the differences in electricity demand and the availability of technologies with low capital costs to satisfy this demand – the investments grow rapidly in the coming decades in the illustrative Supply and Mix scenarios. This suggests that the electricity investments required for the envisioned energy transition in the GEA scenarios may demand a significantly higher share of GDP over the coming decades compared to the current level.

This trend does not necessarily imply that the electricity sector would necessarily take a larger share of the total investments, if the aggregate capital formation in the economy grows at least with the same rate. The trend of aggregate investment in the economy, depicted in Fig. 3, yet suggests that it might not be growing with the pace of the electricity sector. Therefore, the electricity sector should offer an improved return over the next decades in order to attract a higher share of aggregate investment.

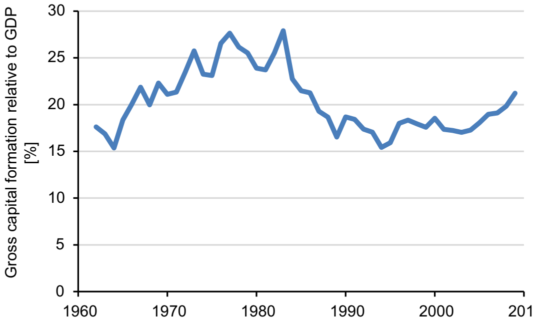

Fig. 3. Gross capital formation relative to GDP (World Bank, 2011).

However, the electricity sector is not the only demander of funds in the continent. The World Bank's “African Infrastructure Country Diagnostic Study” (Foster, 2008) suggests an annual deficit of 38 billion US$ of capital expenditure to redress region's infrastructure, including sectors such as water, sanitation, ICT and roads. This implies that the electricity sector should compete with several other high-priority and potentially more attractive sectors to attract capital.

In order to create more detailed long-term scenarios on electricity investment, we need to assess the different sources of capital for the sector – including their volumes and costs – and make quantified projections for each source. In our context, the capital needed by the electricity sector is distinguished from capital used for other energy investments, such as upstream or end-use, which are likely to have different abilities to provide returns to investment and different sources of finance. Hence in the following we consider the capital supply for the electricity sector only.

Towards this aim, we first analyse the historical financing patterns in Sub-Saharan Africa, and then present ranges of parameter values in order to quantify a number of possible capital supply curves for electricity investment. These supply curves are then further used in the energy scenario analysis of Section 4.

3.2. *Historical trends of investment in Sub-Saharan Africa*

Detailed and comprehensive data on electricity generation investment in Sub-Saharan Africa is scarce. IEA (2003, page 365) estimates that the level for the whole power sector has been below 1% of GDP in the 1990s, with approximately half falling to generation. Foster (2008) suggests that between 2001 and 2005 capital expenditure to power sector has been around 1.1% of GDP. Of this, 40% would have been by the public sector, 12% through official development assistance, 32% from non-OECD FDI and 16% by the private sector. We discuss the characteristics of these financiers in detail.

3.2.1. *Public sector investments*

Most African electricity generators are publicly owned. Of the 45 generating companies that are members to the Union of African Electricity Producers, Distributors and Conveyors (UPDEA), 39 are publicly owned, although from which privatization of four companies is underway. Due to this, African governments have been the largest source for investment in the electricity sector. Briceño-Garmendia et al. (2008) have estimated that public sector investment to the power sector between 2001 and 2005 have been at 1.1% of GDP in oil exporting countries, 0.4% in middle income countries, 0.8% in non-fragile and negligible in fragile low income countries. From this we may assume a range of 0.5% to 1% of GDP as the financing capacity of the public sector in Sub-Saharan Africa.

The public sector may finance its investments with funds from multiple sources. On one hand, if we assume that the public sector is risk averse, the cost of financing should reflect the marginal rate for attracting funds, i.e. the risk-free rate or the cost of borrowing for the government. On the other hand, a government might see additional benefits than the direct monetary return to the electricity investment, i.e. positive externalities, and thus might require lower returns than the borrowing cost for the investment.

Fig. 4 presents estimates on the capital costs of Sub-Saharan Africa's public sector by the World Bank (2010). The risk-free rate implied by lending rates of banks has been fluctuating around 10% during the last decade. The average interest for public and publicly guaranteed debt has, however, been very low, as for most countries in the region the debt involves a notable *grant element*, for which interest or repayment is not necessarily required. A realistic cost of capital assumption for the public sector might thus fall between these measures, and we use a range from 5% to 10% in this study.

3.2.2. *Domestic private sector investments*

African electricity sector has experienced an increase in domestic private investment during the past 15 years, following the privatization of some power companies. Fig. 5 presents investments in electricity generation and, to a smaller extent, transmission and

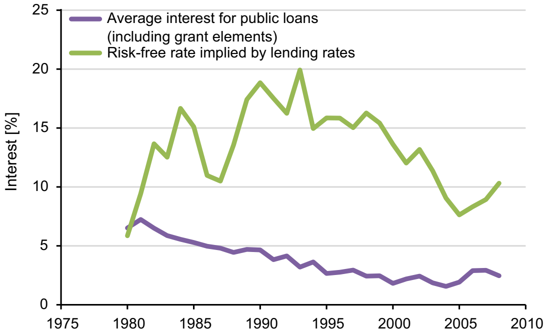

Fig. 4. Capital cost of public sector in Sub-Saharan Africa: risk-free rate implied by lending rates of banks, and average interest for public and publicly guaranteed debt and grants (World Bank, 2010). Note that for the grant element of debt interest payment or repayment is not necessarily required.

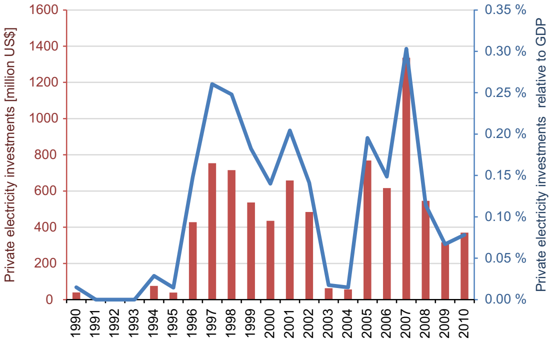

Fig. 5. Private electricity investments in Sub-Saharan Africa, in monetary terms (bars, right scale) and relative to the GDP (line, left scale) of Sub-Saharan Africa (World Bank, 2011).

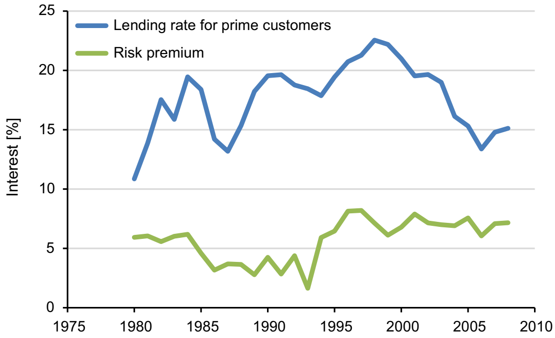

Fig. 6. Average Lending Rates and risk premia (%) for banks' prime customer (World Bank, 2010).

distribution from the World Bank's Private Participation in Infrastructure (PPI) database (World Bank, 2011). As may be seen from Fig. 5, there has been considerable variation in the investment levels between the years, with average investments around 0.15% and the peak at 0.3% of GDP between 2000 and 2010. Should more power sector privatization and regulatory or macroeconomic reforms take place in the future, the potential for private electricity investments could increase. As a result, we assume a broad range from 0.15% to 0.5% of GDP as the financing capacity of the private sector until 2050.

One factor inhibiting the private sector's participation is the cost of financing. Domestic investors should take into account three components for the cost of financing: the risk-free rate, the risk premium, and the spread to borrow from financial markets (transaction costs). Using different definitions of risk, Collins (2006, page 489) provides estimations of equity market return for a subset of African countries, reflected in (Appendix 1). The average African equity premium is in the range of 4.3% to 22.4%, depending on the risk metrics used, with an average of 12%.

For debt financing, investors need to pay an extra spread (the difference between lending and borrowing rates) for the bank loans to cover the operational costs and mark-ups in the banking sector. Fig. 6 presents the trend of lending rates and risk premia for prime customers in Sub-Saharan Africa since 1980. The average risk premium for lending in the recent years has been around 7%, while the lending rate has fluctuated in the range of 15% to 20%. Combining the average of these premia to the range of risk-free rates assumed in Section 3.2.1 gives ranges from 17% to 22% for equity, and from 12% to 17% for borrowing.

3.2.3. Foreign direct investment (FDI) in Africa

FDI to Africa has historically accounted for only a small fraction of GDP. However, during the last decades the conditions have changed and the ratio of FDI to GDP has increased, with a record level of 7.7% of GDP in 2004. Still, an important fraction of inward FDI to Africa is allocated to upstream oil, gas and mining sectors.

The future trend of FDI will depend on political stability, domestic policies, competing regions' attractiveness, and the global economic situation (Lamech and Saeed, 2003). FDI to Africa is a small fraction of global FDI flow; therefore, we assume that there is, in principle, no cap on the investment capacity to the region as long as the regulations and investment climate of the region are favourable and the projects are offering attractive risk/return profiles.[10]

The cost of capital differs between domestic and foreign private investors. The foreign investor holds a globally diversified portfolio, and investing in Africa's electricity sector can be attractive because it contributes to further portfolio diversification. Yet, foreign investors are also exposed to extra risks such as transfer and currency risks. While the diversification effect reduces the risk-premium, the transfer and currency risks increase the premium.[11] Our capital costs estimate for FDI consists of a baseline rate for foreign investors and a risk premium, which includes equity and country premia. We choose the baseline rate close to average global rates, e.g. 6 month LIBOR[12] for dollars, which has been fluctuating around an average of 4.5% since 1990.

To estimate the extra premium component we refer to existing estimates. Damodaran (2011) provides country risk premia for a group of countries based on country ratings by Moody's. Unfortunately, not many African countries are present in his estimates. However, for a basket of countries with closer characteristics to Sub-Saharan Africa the risk premium is generally between 7% and 14%. Additional perspective can be gained from Fig. 7, which compares the risk premia estimates of Damodaran (2011) and expert survey results of Fernandez et al. (2011) against the GDP per capita of a country. For countries with GDP (PPP) per capita similar to most countries in the region, the risk premia mainly fall to the range from 8% to 14%. The total cost of capital would thus range between 13% and 18%. This is roughly consistent with Odenthal and Zimny (1999), who report the annual returns to US FDI into Africa for 1983–1997 to range between 5.6% and 35.3%; although the ex-ante and ex-post nature of these two ranges, correspondingly, should be borne in mind, as noted in Section 2.2.

3.3. A multi-source capital supply curve

To formulate the limitations in access to funds, we use a discrete multi-step capital supply curve consisting of three representative financiers: the public sector, domestic private investors and foreign investors.[13] One key underlying assumption to motivate a steeply rising capital supply costs is that the ability of a single sector in the economy to attract funds is limited. Different sectors in the economy are competing to attract funds but at the margin they propose similar risk/return profiles. Since investors are risk-averse they will diversify their investment among different sectors. Thus, no single sector can absorb a large share of the capital in an economy, unless it pays an extra-ordinary excess returns, which would in turn imply a high cost for capital for that sector. Because the electricity sector's ability to pay high returns is likely to be different from that of e.g. the upstream energy sector (oil and gas), our analysis separates these sectors and considers the capital constraints in the electricity sector only.

Estimating financial constraints at a regional level is not a straightforward task and large uncertainties are obviously present

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[10] To engage in a large-scale and irreversible investment project, such as a power plant, investors should carry a large amount of up-front fixed costs. Any incentive which reduces the risks associated with low return to investment can boost the tendency to enter this market. For example, long-term purchase agreement, guaranteed fuel contracts, compensation of unused capacity, extra payment for generating electricity from clean sources, allowing for charging higher price in peak demand episodes, and tax exemptions can all improve the expected rate of return of the project. Lamech and Saeed (2003) mention adequate cash flow and rule of law among factors which international investors consider for investing in the power sector.

[11] Since the foreign investor holds a different portfolio, it is not clear a priori if the expected risk premium for her is higher or lower than the domestic private investor. Their relative risk premium depends on the ratio of domestic versus international CAPM risk as well as risks imposed to foreign investors.

[12] London Interbank Offered Rate (LIBOR) is a standard indicator for the rate in which banks can lend or borrow from each other.

[13] The steps in the graph are only an illustrative example for a general space of discount rates combinations. In reality, the domestic rates can be higher or lower than the foreign ones.

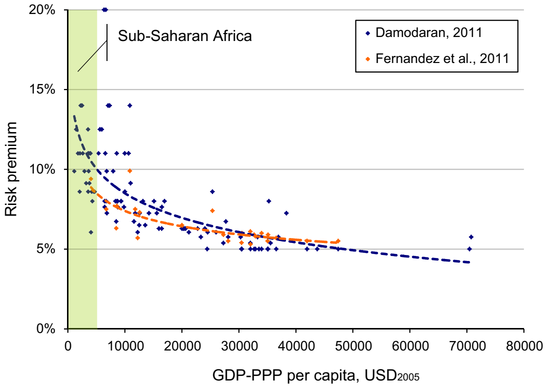

Fig. 7. Estimates of risk premia for foreign investment plotted against the GDP (PPP) per capita of the country. In Sub-Saharan Africa the GDP(PPP) per capita in 2005 ranged mainly between 200$ (Zimbabwe) and 5500$ (Namibia), while the wealthier countries of Equatorial Guinea, Gabon, Botswana and South Africa ranged between 9000$ and 13,000$.

in our estimates. Moreover, the state of the economy changes over time and the curve has a dynamic nature. To overcome these aspects, we define separate scenarios with different capital cost curves, based on the combinations of parameter ranges estimated in Section 3.2, and use one of these curves as an illustrative case. The set of capital cost curves for Sub-Saharan Africa are presented in Fig. 8, with the illustrative case highlighted. As the set of parameters used for the curves is rather broad, the results from using the whole set gives a good indication of the robustness of the results, while the illustrative case allows for a specific examination of one particular case.

4. African energy scenarios with capital supply

In order to quantitatively assess the effect of limited capital supply and high required returns on electricity investment, we present energy scenarios for Sub-Saharan Africa up to 2050 with various assumptions on the available capital. Towards this aim, the capital supply curves from Fig. 8 were implemented into an energy system model.

4.1. Modeling framework

The model used here is a linear cost optimization model with perfect foresight developed by Krey and Riahi (2009), similar to common modelling frameworks such as MESSAGE (Messner and Strubegger, 1995; Riahi et al., 2007), TIMES (Loulou and Labriet, 2008) and MARKAL (Loulou et al., 2004). Due to this similarity, the technical implementation of the capital supply curve to other models using the same solution concept is straightforward. Details on the technical implementation of the capital supply curve are provided in Appendix 2.

The model includes a simplified, single-region representation of the energy system of Sub-Saharan Africa, with a focus on the electricity sector. Given a projection for future energy demand, available energy resources, technology specifications and costs for resource extraction, transformation and energy end-use; the model finds a least-cost solution to fulfil a projected energy demand, including costs from energy supply, distribution and demand side technologies. The model input data was calibrated to the illustrative GEA-Mix scenario (Riahi et al., 2012). The model is calibrated to 2010, after which the model is free to select the optimal way of satisfying the projected energy demand.

The selected GEA scenario includes a global climate change mitigation target, aiming at atmospheric greenhouse gas concentrations of 450 ppm CO_2-eq by 2100, that is reached under a globally coordinated climate policy and emission markets. The scenario assumes a moderate pathway for demand growth and technological development, and an efficient, globally uniform emission pricing with a carbon value of 34$/t$CO_2$ in 2020 and a 5% annual growth thereafter. Because of the emission pricing, coal power is phased out rapidly by 2030 in this scenario, and replaced by a portfolio of hydro, solar (both CSP and PV), biomass, nuclear and wind power, including a small share of gas power with CCS after 2030. As a result the share of renewables in the electricity portfolio rises rapidly from 24% in 2005 to 61% in 2030, and further to 78% in 2050.

4.2. Energy scenarios with capital supply

To quantify the effect of capital supply on energy investment, we present both a non-capital constrained scenario with a flat 5% discount rate and scenarios with capital supply curves parameterized according to Fig. 8. Comparing the capital supply curves to the investments in the GEA-Mix scenario in Fig. 2 suggests that if investments were to be made as in the original scenario, costlier capital would have to be used starting from 2020 with every capital supply curve of Fig. 8. However, introducing a higher marginal cost for capital to the model is likely to affect the cost-optimal technology portfolio and thus alter the amount of invested capital, even if electricity output is kept constant between the scenarios.

A baseline scenario without climate policy provides a good point of departure for the scenario analysis. Electricity investments remain at estimated historical levels, around 0.7% of GDP, in the baseline scenario without capital constraints. With our range of assumptions on the capital supply, the capital constraint affects investments only with some of the assumed capital supply curves. Moreover, in these cases the effect of costlier capital is reduced by introducing a larger share gas power to the technology portfolio. The effect of capital supply is therefore only modest in the baseline.

In the scenarios with climate policy, however, the effect of capital constraints is much more pronounced. Fig. 1 suggested that with a high cost of capital, cost-minimizing technology selection favours gas power – the least capital intensive centralized generation technology – even with relatively high emission prices. This is also observed from Fig. 9, which presents the scenario with the illustrative supply of capital. With constrained capital supply, gas-based electricity is the main generating technology

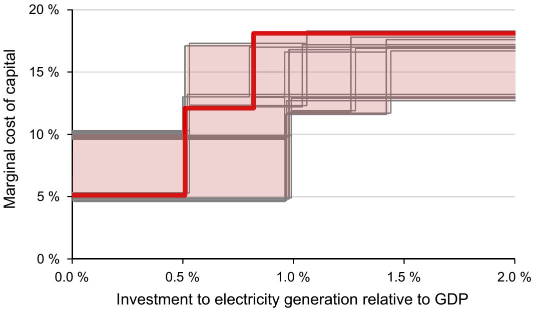

Fig. 8. The set of estimated capital cost curves. Individual curves are slightly shifted to improve visibility and presented for illustration purposes, and thus should not be considered separately but as a range. An illustrative case is marked with a thick red line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

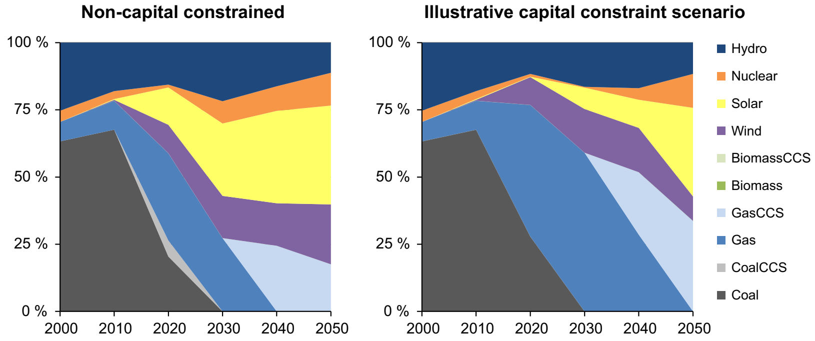

Fig. 9. The shares of electricity generating technologies in terms of electricity output in a scenario with the illustrative capital supply curve.

until 2030.[14] and the introduction of renewables is delayed by more than ten years. This effect occurs consistently with all assumed capital cost curves, as can be seen from Fig. 10.

Consistent with a lower capital intensity of generating capacity, the monetary amount of electricity investments is also smaller in the capital constrained cases, as Fig. 11 presents. Although the electric power output capacities are nearly equal across scenarios, investments in monetary terms are roughly halved between 2020 and 2030 in all of the scenarios with higher cost of capital.

An interesting feature is that the change in the marginal price of electricity is far less dramatic, as can be observed from Fig. 12. This stems from technology substitution, through which the model is able to compensate the higher cost of capital by selecting less capital-intensive technologies. If demand price elasticity were considered, the change in demand would therefore be only minor.

The delayed introduction of non-fossil electricity technologies leads obviously to higher emission levels. As Fig. 13 presents, costlier capital renders the pricing of emission – equal in all presented scenarios – less effective, delaying the emission reductions and leaving the cumulative energy-based CO_2 emissions between 2020 and 2050 of Sub-Saharan Africa 43% higher in the illustrative case than in the case without capital constraints.

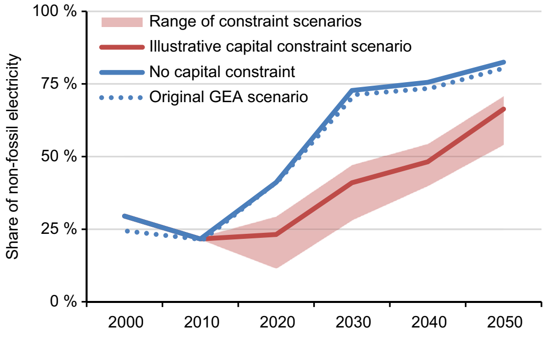

Fig. 10. Share of non-fossil electricity (nuclear and renewables) in electricity generation in Sub-Saharan Africa.

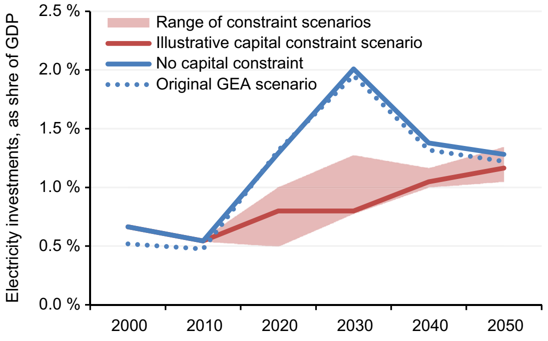

Fig. 11. Monetary amount of electricity generation investments as a share of GDP.

4.3. Capital supply and climate policy

An underlying assumption in the scenarios was a single, global price for emissions, implemented either through harmonized emission taxes or a global emission market in which Sub-Saharan Africa acts as a price taker. Both options lead effectively to a price-based emission control in Sub-Saharan Africa. As higher capital costs diminish the impact of a price-based control of emissions, the differences in capital costs across countries needs to be taken into account when planning or analysing global climate policy. Assuming a too high investment capacity, or equivalently a too low discount rate, one overstates the amount of realized emission reductions with a price based control (emission tax), or understates the resulting market price of emissions with a quantity based control (cap-and-trade).

To portray the above proposition in our modelling setting, Fig. 14 presents how much the price of emissions would have to be increased in the capital constrained scenario in order to reach the cumulative emission level between 2020 and 2050 of the non-capital constrained case. In all scenarios, the presented emission price is set for the year 2020, and is assumed to increase annually by 5% thereafter. In the modelled case of Sub-Saharan Africa with the illustrative capital supply curve, the price of emissions would have to be increased by roughly 60%, from 34\$/tCO_2 to 54\$/tCO_2, to reach the cumulative emission level of the non-capital constrained scenario. Looking from another perspective, without capital constraints the higher 54\$/tCO_2 emission price would reach emission levels that are cumulatively 30% lower than with the lower 34\$/tCO_2 price.

Global climate policy might, however, also help in reducing the capital scarcity in developing countries. If climate policy is pursued effectively through a global cap-and-trade framework (or harmonized emission taxes with transfers), an equitable effort sharing – i.e. the allocation of emission allowances (or the amount of transfers) to countries – has been projected to involve large trade flows of emission allowances from developing countries to the

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[14] Capital constraints for gas pipeline investments were not considered in this study, although capital scarcity similar to that of electricity generation might inhibit investments to gas distribution.

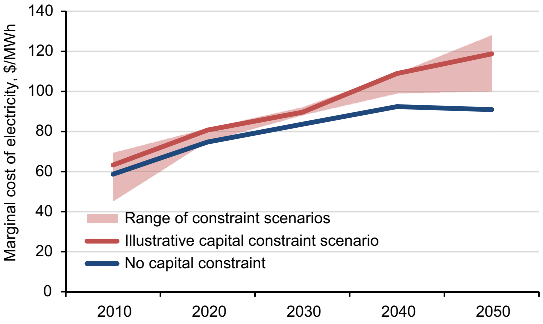

Fig. 12. The marginal cost of electricity generation [$/MWh].

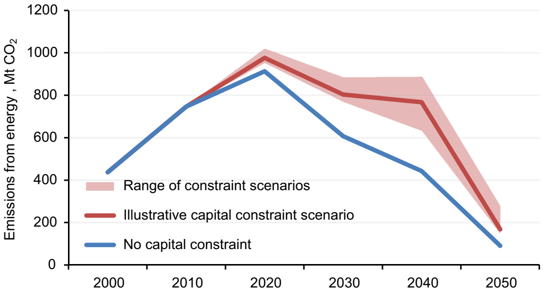

Fig. 13. Energy-based CO_2 emissions (including electricity generation, industry, transportation and other fuel use) in Sub-Saharan Africa.

developed ones. Past effort sharing studies (e.g. den Elzen et al., 2005, 2008; Persson et al., 2006; Ekholm et al., 2010) have suggested the trade flows for Africa between 2020 and 2050 might range from 0.1% to 4.9% of Africa's GDP. Should this revenue from selling emission allowances be available in part for electricity investments, the problem of capital constraints might be alleviated.

There are, however, some obstacles for this. First, it depends on the how climate policy is formulated—specifically who initially owns the African emission allowances and whether the owner is willing to use the emission trading revenues for electricity investments. This could be in principle solved by allocating the allowances to the government, and earmarking the revenues for investment, although the outcome might not be the most socially beneficial.

Second, emission reductions are prerequisite for the emission trading income. Hence the reductions – and investment to clean technologies – have to precede the trade revenues. Yet, in order to use the trade revenue for investment a contrary course of action would be required. If the energy producers are cash constrained, as we here assume to be, they might be unable to carry out the initial investments and realize the revenues from emission trading. In such a case the initial investment would have to come from some other source, e.g. from official development assistance, climate funds (e.g. Carraro and Massetti, 2012) or a global institution purchasing emission allowances (Bradford, 2004). If the obstacles of the first investments are cleared, the future revenues from emission trading and savings from fuel costs could be used for subsequent investments.

As a quantitative example, if the difference in emission levels between the capital constrained and non-constrained case, presented in Fig. 13, is valued with the emission price projection used, the monetary value amounts on average to 0.28% of Sub-Saharan Africa's GDP between 2020 and 2050, with the highest value of 0.6% in 2030—the year with the highest investment gap. Having this capital available for electricity investments the problem of constrained capital would almost be lifted, and the non-capital constrained scenario might be followed. This can, however, be a two-edged solution. Although emission trading could bring additional revenue, it also creates an additional source of uncertainty regarding the price of emissions. Therefore the applicability of using emission trading revenues to supply capital for investments might rest on the predictability of climate policy and stability of emission prices.

5. Summary and conclusions

In this paper we have analysed the effect of capital supply constraints on energy scenarios and implemented the concept in an energy system model for Sub-Saharan Africa. We first discussed conceptually the causes for and effects from capital supply and capital costs, and provided estimates for available capital and required rates of return for different financiers. Reflecting on the energy scenarios of Global Energy Assessment (Riahi et al., 2012), it seems that relatively costly capital would have to be used should a global climate policy and emission pricing affect the region. For analysing this explicitly, we calculated scenarios of electricity generation for Sub-Saharan Africa that take the scarceness of capital into account.

A wide range of possible capital cost curves were introduced into an energy system model for Sub-Saharan Africa, and the resulting scenarios differed notably from a non-capital constrained case. With higher cost of capital, the selection of cost minimizing technologies favours less capital-intensive production methods. In the scenarios this meant that electricity will be produced primarily with gas power plants up to 2030, instead of renewables, despite the carbon prices. Consequentially, the investments in monetary terms were considerably lower, and CO_2 emissions higher, than in the non-constrained scenario. Yet, due to the flexibility arising from technology selection, the marginal production costs of electricity were increased only slightly. All these findings proved to be very robust, as a number of different capital supply curves were used in the model.

From the viewpoint of climate policy, an important implication of these results is that, keeping other factors fixed, the emission reductions induced by a given emission price are decreased with a high cost for capital. Conversely, for a quantity-based control of emissions, higher cost of capital increases considerably the

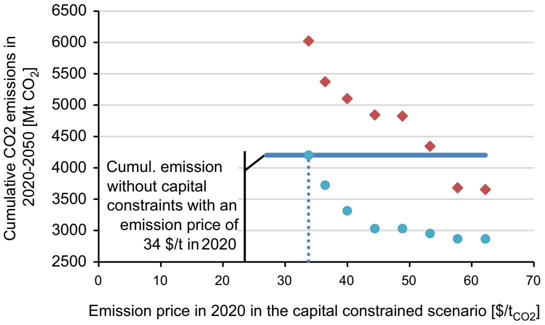

Fig. 14. Cumulative energy-based CO_2 emissions between 2020 and 2050 in *capital constrained* (red points) and *non-capital constrained* (blue points) scenarios with different emission prices. The price is set for 2020 and increases annually by 5% thereafter. The horizontal blue line indicates the cumulative emission level of a *non-capital constrained* scenario with an emission price of 34 $/$tCO_2$ in 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

emission price required to reach an emission target. In our scenarios of Sub-Saharan Africa, the price level had to be increased by 60% in the capital constrained scenario in order to reach the emission levels of the non-constrained case. This has important implications for both policy and modelling, because disregarding this effect would lead to either a considerable overestimation of emission reduction potentials that a given price incentive could achieve, or an underestimation of economic consequences a quantity target might inflict. Models and scenarios should either take the capital constraints or higher risk premia into account; or to allow non-uniform emission prices between regions in order to reach the desired regional emission levels.

To solve the capital constraint problem, and thus be able to follow a more efficient climate scenario, governments' financial capacities to invest should be increased, or the investment risks of the private sector should be hedged. Climate funding, e.g. revenue from selling emission allowances on a global emission market, has been suggested as a solution to the former. However, in the case of electricity generation this would not be a complete solution as the investment capital is required prior to the emission reductions, and then subsequent emission trading with the unused allowances. Therefore, another source of capital should be used for the first investments, while the emission trading revenue and savings from fuel costs could be used to fund subsequent investments.

Although we looked at the African electricity sector only, we think that similar capital constraints – and their implications – can affect also other regions and sectors, though not necessarily to the same extent. In future studies, the work might be extended e.g. by looking at the problem from a general equilibrium framework. Also, having better grounded estimates of the present and future capital supply curves would be an important improvement, although our findings proved to be robust for a large range of capital supply curves.

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Appendix 1. Africa's equity risk premium

See Table A1.

Table A1
Equity risk premium in African markets (%pa) (Collins, 2006).

Market	CE_{β}^{D}	CE_{β}	$CE_{\Sigma\mu}$	CE_{σ}	CE_{Skew}	CE_{VaR}
S. Africa	10.78	8.88	14.95	14.45	39.13	17.46
Egypt	7.01	4.77	13.27	14.26	9.10	15.15
Zimbabwe	4.18	4.02	21.77	21.26	25.56	26.15
Morocco	3.95	3.51	7.94	8.86	22.70	8.46
Mauritius	4.60	3.50	7.62	8.09	7.56	8.60
Tunisia	4.81	3.02	11.46	11.76	13.27	13.85
Nigeria	5.57	3.67	10.81	11.93	17.39	12.38
Botswana	5.02	3.90	8.98	9.99	16.53	9.35
Kenya	4.64	3.31	10.92	10.54	47.56	11.62
Ghana	4.21	3.32	11.42	12.55	24.13	13.80
Namibia	4.81	4.84	13.77	15.01	23.27	17.14
Average	**5.42**	**4.25**	**12.08**	**12.60**	**22.38**	**14.00**

Appendix 2. Specifying required rates of return in cost-optimization models

A prerequisite for a successful and profitable investment is that the returns to investment are higher than the cost of capital used. Modelling the returns to investment with a cost-minimizing linear programming (LP) tool (such as MESSAGE, TIMES, MARKAL or our model used here) is however not directly possible, as prices are not endogenous variables in the model, but extracted from the marginal values from the optimization problem. In addition, the models discount all costs that are to be minimized using a single discount rate, while multiple rates would be necessary to implement the capital cost curves of Fig. 8. Due to these impediments, an approximation has to be used. This appendix describes the method used in the paper to implement a capital cost curve into a cost-minimizing LP model.

The internal rate of return (IRR) from an investment I with a lifetime of T is

$$IRR = \left\{ r \,|\, -I + \sum_{t=1}^{T} (1+r)^{-t} \pi_t = 0 \right\} \tag{A2.1}$$

where π_t is the profit less capital costs from the investment in year t. The profits may obviously fluctuate, but let us simplify this with an ex-ante assumption that they increase or decrease with a constant factor ρ, i.e. $\pi_t = (1+\rho)\,\pi_{t-1}$, and insert this into Eq. (A2.1).

We wish to approximate a given cost of capital, or more accurately a required rate of return, r in a model that uses a general discount rate r_M. We do this by modifying the investment cost into I_2, which is to be used with in the linear cost-minimization model with the discount rate r_M. For the approximation to be accurate, the linear model should produce the same prices, and therefore also the profit schedule $\{\pi_t\}$, than a case what would take place if the true rate of return r would have been used. Therefore we may write an IRR equation for the approximation, using also the assumption $\pi_t = (1+\rho)\pi_{t-1}$, resulting in

$$-I_2 + \pi_1 \sum_{t=1}^{T} \left(\frac{1+\rho}{1+r_M} \right)^t = 0 \tag{A2.2}$$

Solving for Eqs. (A2.1) and (A2.2) then yields

$$\gamma = \frac{I_2}{I} = \frac{(\rho - r)(((1+\rho)/(1+r_M))^T - 1)}{(\rho - r_M)(((1+\rho)/(1+r))^T - 1)}$$

The coefficient γ, with which the investment costs in the linear model have to be modified, still depends on ρ, the rate of change of profits. Two natural options for choosing a value of ρ to be used include zero and the model discount rate r_M, often at 5%. As γ is increasing in ρ, a too high value of ρ exaggerates the effect of capital costs, and vice versa. Seeking to avoid over-exaggerating the results, in this study we have chosen a constant $\rho = 0$ as a conservative estimate. This gives a more simple formula

$$\gamma = \frac{I_2}{I} = \frac{r(1-(1+r_M)^{-T})}{r_M(1-(1+r)^{-T})}$$

with which all investment costs that are executed with the cost of capital r are inflated.

References

Awerbuch, S., 1993. The surprising role of risk and discount rates in integrated resource planning. The Electricity Journal 6 (3), 20–23.

Acemoglu, D., Zibotti, 1997. Was Prometheus unbound by chance? risk, diversification and growth. Journal of Political Economy 105 (4), 709–751.

Bencivenga, V.R., Smith, B., 1991. Financial intermediation and endogenous growth. Review of Economic Studies 58 (2), 195–209.

Bernheim, B.D., 2002. Chapter 18 Taxation and saving. In: Auerbach, A.J, Feldstein, M (Eds.), Handbook of Public Economics, 3. Elsevier, pp. 1173–1249.

Blackman, A., Wu, X., 1999. Foreign direct investment in China's power sector: trends, benefits and barriers. Energy Policy 27 (12), 695–711.

Briceño-Garmendia, C., Smits, K., Foster, V., 2008. Financing Public Infrastructure in Sub-Saharan Africa: Patterns and Emerging Issues, AICD, Background Paper 15. World Bank, Washington, D.C..

Bradford, D.F., 2004. Improving on Kyoto: Greenhouse Gas Control as the Purchase of a Global Public Good, CEPS Working Paper 96, Princeton University, Department of Economics, Center for Economic Policy Studies.

Cambini, C., Rondi, L., 2010. Incentive regulation and investment: evidence from European energy utilities. Journal of Regulatory Economics 38 (1), 1–26.

Carraro, C., Massetti, E., 2012. Beyond Copenhagen: a realistic climate policy in a fragmented world. Climatic Change 110, 523–542.

Clague, C., Keefer, P., Knack, S., Olson, M, 1999. Contract-intensive money: contract enforcement, property rights, and economic performance. Journal of Economic Growth 4 (2), 185–211.

Collins, D., 2006. Measuring the cost of equity in frontier financial markets. In: Murinde, V. (Ed.), Research in Accounting in Emerging Economies. Macmillan India Limited., Bangalore.

Damodaran, A., 2011. Country default spreads and risk premiums, ⟨http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/ctryprem.html⟩, cited 16.6.2011.

den Elzen, M., Lucas, P., van Vuuren, D., 2005. Abatement costs of post-kyoto climate regimes. Energy Policy 33 (16), 2138–2151.

den Elzen, M.G.J., Lucas, P.L., Van Vuuren, D.P., 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations. Climatic Change 90 (3), 243–268.

Ekholm, T., Soimakallio, S., Moltmann, S., Höhne, N., Syri, S., Savolainen, I., 2010. Effort sharing in ambitious, global climate change mitigation scenarios. Energy Policy 38, 1797–1810.

Estache, A., Pinglo, M. E., 2004. Are returns to private infrastructure in developing countries consistent with risks since the Asian crisis?, Policy Research Working Paper Series 3373, The World Bank.

Fama, E.F., French, K.R., 1993. Common risk factors in the returns on stocks and bonds. Journal of Financial Economics 33 (1), 3–56.

Fernandez, P., Aguirreamalloa, J., Avendaño, L.C., 2011. Market Risk Premium Used in 56 Countries in 2011: A Survey with 6014 Answers. Working Paper WP-920, IESE Business School, University of Navarra.

Fritz-Morgenthal, S., Greenwood, C., Menzel, C., Mironjuk, M., Sonntag-O′Brien, V., 2009. The global financial crisis and its impact on renewable energy finance. United Nations Environment Program.

Foster, V., 2008. Africa Infrastructure Country Diagnostic, Overhauling the Engine of Growth: Infrastructure in Africa. World Bank.

Galindo, A., Schiantarelli, F., Weiss, A., 2007. Does financial liberalization improve the allocation of investment? micro-evidence from developing countries. Journal of Development Economics 83 (2), 562–587.

Hail, L., Leuz, C., 2006. International differences in the cost of equity capital: do legal institutions and securities regulation matter? Journal of Accounting Research 44 (3), 485–531.

IEA, 2003. World Energy Investment Outlook 2003. Organisation for Economic Co-operation and Development and International Energy Agency, Paris, France.

Jensen, M.C., Meckling, W.H., 1976. Theory of the firm: managerial behavior, agency costs and ownership structure. Journal of Financial Economics 3 (4), 305–360.

Krey, V., Riahi, K., 2009. Risk Hedging Strategies under Energy System and Climate Policy Uncertainties, Interim Report IR-09-028.

La Porta, R, Lopez-de-Silanes, F, Shleifer, A, Vishny, R, 1998. Law and Finance. Journal of Political Economy 106, 1113–1155.

Levine, R, 1997. Financial development and economic growth: views and agenda. Journal of Economic Literature 35 (2), 688–726.

Lintner, J., 1965. The valuation of risk assets and the selection of risky investments in stock portfolios and capital budgets. Review of Economics and Statistics 47 (1), 13–37.

Lamech, R., Saeed, K., 2003. What International Investors Look For When Investing In Developing Countries; Results from a Survey of International Investors in the Power Sector, Energy and Mining Sector Board Discussion Paper no. 6, The World Bank, Washington, DC.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL family of models. IEA Energy Technology Systems Analysis Programme.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model—Part I: Model structure. Computational Management Science 5, 7–40.

Love, I., 2003. Financial development and financing constraints: international evidence from the structural investment model. Review of Financial Studies 16 (3), 765–791.

Myers, S., Majluf, N.S., 1984. Corporate financing and investment decisions when firms have information that investors do not have. Journal of Financial Economics 13 (2), 187–221.

Messner, S., Strubegger, M., 1995. User's Guide for MESSAGE III. International Institute for Applied Systems Analysis, Technical Report WP-95-69.

Modigliani, F., Miller, M., 1958. The cost of capital, corporation finance and the theory of investment. American Economic Review 48 (3), 261–297.

Mukherjee, M., Pratap, K.V., 2011. The Impact of the Global Financial Crisis on Investments in the Electric Power Sector. The World Bank and ESMAP, Report No. 56849-SAS.

Odenthal, L., Zimny, Z., 1999. Foreign Direct Investment in Africa: Performance and Potential, UNCTAD/ITE/IIT/Misc. 15, United Nations Conference on Trade and Development.

Persson, T.A., Azar, C., Lindgren, K., 2006. Allocation of CO_2 emission permits—Economic incentives for emission reductions in developing countries. Energy Policy 34, 1889–1899.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 887–935.

Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., van Ruijven, B., van Vuuren, D.P., Wilson, C., 2012. Energy Pathways for Sustainable Development. In: The Global Energy Assessment: Toward a More Sustainable *Future*. IIASA, Laxenburg. Austria and Cambridge University Press, Cambridge UK.

Servén, L, 2003. Real-exchange-rate uncertainty and private investment in LDCS. Review of Economics and Statistics 85 (1), 212–218.

Stiglitz, J.E, Weiss, A, 1981. Credit rationing in markets with imperfect information. The American Economic Review 71 (3), 393–410.

World Bank, 2010. World development indicators and global development finance database, ⟨http://data.worldbank.org/data-catalog/global-development-finance⟩.

World Bank, 2011. Private participation in infrastructure (PPI) project database, ⟨http://ppi.worldbank.org⟩.

ARTICLE V

Determinants of household energy consumption in India

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Determinants of household energy consumption in India

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ABSTRACT

Improving access to affordable modern energy is critical to improving living standards in the developing world. Rural households in India, in particular, are almost entirely reliant on traditional biomass for their basic cooking energy needs. This has adverse effects on their health and productivity, and also causes environmental degradation. This study presents a new generic modelling approach, with a focus on cooking fuel choices, and explores response strategies for energy poverty eradication in India. The modelling approach analyzes the determinants of fuel consumption choices for heterogeneous household groups, incorporating the effect of income distributions and traditionally more intangible factors such as preferences and private discount rates. The methodology is used to develop alternate future scenarios that explore how different policy mechanisms such as fuel subsidies and micro-financing can enhance the diffusion of modern, more efficient, energy sources in India.

1. Introduction

Providing clean and affordable energy reliably for poor households in developing countries is an important prerequisite in the fight against poverty. Even though rural households often have an easy access to traditional forms of energy—firewood, charcoal and agricultural residues—to fulfil their basic energy needs, these fuels carry adverse effects, such as emissions of particulate matter that are harmful to health, deforestation and environmental degradation. The greater time needed for gathering, transporting and using these fuels also reduces the prospects for using this time in more productive work or education. In addition, as women and children are more likely to suffer from many of these adverse effects, the issue has an important gender and equity dimension (Pachauri, 2004b). The low efficiency associated with the direct combustion of biomass in traditional devices is also sub-optimal from a societal and technical perspective (Reddy, 2003).

A large concentration of people relying on the traditional forms of energy can be found in India, and improving the access of the poor to modern energy has been on the agenda of the government of India since independence. Electrification has especially received much attention within the policy arena, and a summary of past electrification measures can be found in Bhattacharyya (2006). Kerosene and LPG—the main modern cooking fuels in India—have also been subsidized since long, although there has been pressure to limit these subsidies more recently (Gangopadhyay et al., 2005). However, as electricity is rarely used for cooking or heating in India, electrification cannot be seen as an effective solution for reducing the consumption of traditional fuels and the above-mentioned detrimental impacts associated with their use. It should be noted, though, that electricity is required for sufficient lighting and associated with several additional benefits, e.g. improved education and employment possibilities (Kanagawa and Nakata, 2008).

Literature on household energy requirements in developing countries, particularly for the case of India, is extensive. The traditional view on fuel choice has been the "energy ladder" approach (e.g. Leach, 1992), according to which households switch to more convenient energy forms as their disposable income increases. A partial critique of this approach has been presented by Masera et al. (2000), who observed from data on rural Mexican energy consumption that households do not ascend a "ladder" but rather follow a "stacking" procedure, i.e. traditional fuels are not completely discarded with rising income, but rather used in conjunction with modern fuels due to cultural preferences.

The importance of income as a factor affecting fuel use is, however, apparent, even in the case where the switch to modern fuels is not always complete. For Indian consumers, Pachauri (2004a) found that the statistically most significant factors determining households' energy consumption were income and location, whether rural or urban. However, the factors likely to

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affect fuel choices vary by location, financial circumstances and household preferences. Therefore, the energy choices of consumers with different income and location should be assessed separately in energy policy analysis, in contrast to the "representative consumer" approach normally followed in most economic models.

There have been some previous attempts on formal modelling of household energy choices, using a linear cost-minimization solution concept, e.g. by Kanagawa and Nakata (2007, 2008) for the case of India, and by Howells et al. (2005) for an African village. These studies, however, suffer from a number of shortcomings, for instance they disregard consumer heterogeneity, the high discount rates of the poor and differing preferences. A system-dynamic model for India (van Ruijven, 2008, Chapter 6) addresses these issues partially, but does not account fully for all the factors mentioned above. Studies employing logit models of fuel choices have also been conducted. E.g. Reddy (1995, 1996) distinguishes between different income groups in their fuel choice models for Bangalore, India. However, they do not carry out any policy analysis or provide recommendations for the future based on their model results.

This paper therefore intends to establish a stronger framework for modelling the energy choices of households, by explicitly accounting for the heterogeneous economic conditions and preferences of populations living in rural and urban settings, in, order to analyze effective policy choices to improve the penetration of modern cooking fuels among the poor. We start by discussing existing energy consumption patterns in Indian households, based on data from a nationally representative consumer survey. A basic, microeconomic choice model is then presented, serving as the backbone of our energy choice model. This is further expanded to incorporate different practical determinants relevant to the choice problem in the model. We also present a sensitivity analysis for certain key parameters included in the model. The choice model developed is then implemented as the MESSAGE-Access model within the MESSAGE linear cost optimization framework (Messner and Strubegger, 1995). As an application of the MESSAGE-Access model, the effect of fuel subsidies and improved financing options on the future adoption of modern cooking fuels in India is assessed in the final section of the paper.

2. NSSO survey on household energy consumption

This study is largely based on a large consumer survey, carried out by National Sample Survey Organisation (NSSO) of India between 1999 and 2000 (NSSO, 2000). In the survey the respondents were asked to state, among others, their energy consumption for different energy forms in energy and expenditure terms in the past 30 days. In addition to expenditure, the survey also includes home-grown fuel sources for traditional fuels. The NSSO surveys, which involve the energy questionnaire every five years, involve a large sample of households and cover the whole of India, and thus can be assumed to be representative of the nation as a whole.

The energy consumption data from the 1999/2000 survey has already been analyzed extensively in a number of papers, and a more in-depth analysis can be found e.g. in Bhattacharyya (2006), Gangopadhyay et al. (2005) and Pachauri (2007). The survey data have also been used to estimate the elasticities of different energy forms by Gundimeda and Köhlin (2008); to identify barriers for improving energy efficiency by Reddy (2003); to construct a measure of energy poverty by Pachauri (2004b) and to model urban fuel choices by Farsi et al. (2007).

As households with different socioeconomic status are likely to make differing choices regarding their energy use, the household heterogeneity should be taken into account in models. For this differentiation, the households' expenditure level and nature of surroundings—whether urban or rural—were used, as these factors were identified to be the statistically most significant determining households' energy consumption patterns by Pachauri (2004a). The NSSO survey data were therefore split into 10 consumer groups—labelled R1–R5 for the rural and U1–U5 for the urban population, with expenditure rising with the group number—consisting of expenditure quintiles for the urban and rural populations.

From Fig. 1, which portrays the survey data split between the consumer groups, we can see that the energy consumption patterns of the groups are very distinct. The rural population relies largely on traditional fuels. Even though electricity, kerosene and LPG consumption increases with rising expenditure levels, traditional fuel use also increases in absolute terms and dominates the fuel mix of rural households, even after accounting efficiency differences. On the other hand in urban areas the switch from traditional to modern fuels is more apparent as the absolute amount of traditional energy consumption is decreasing with rising expenditure.

An interesting feature can also be seen from an analysis of the sources of firewood, the main traditional fuel source consumed, illustrated in Fig. 2. The figure shows that for some 20% of households even in the lowest expenditure quintile purchase their firewood. This would thus indicate that the market for traditional fuels is functional even within the lowest expenditure

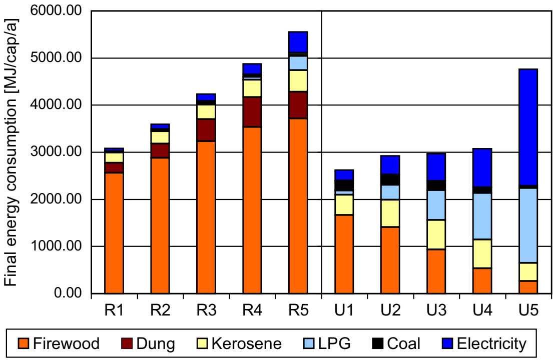

Fig. 1. Household final energy consumption (MJ/cap/a) of the 10 consumer groups.

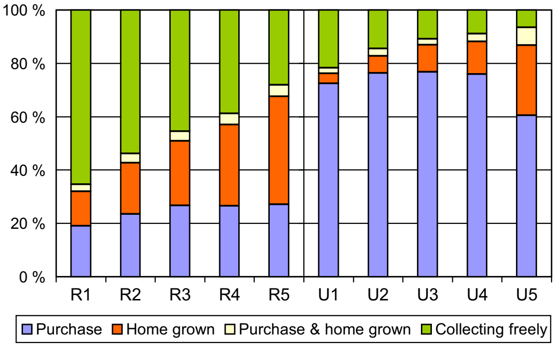

Fig. 2. Sources of firewood of the 10 consumer groups.

category. This, in turn, implies that traditional fuel consumption always carries a cost—at least an opportunity cost—regardless of whether collected freely or bought, as the collected firewood could also be sold. In the presence of the opportunity cost, cost minimizing behaviour can then be assumed with all households.

As the NSSO data does not indicate the purpose for which each fuel is being used, the consumption data have to be further divided among the different energy services. For splitting kerosene consumption for lighting and cooking, the approach from Gangopadhyay et al. (2003) was adopted, grouping consumers by their stated main lighting and cooking fuels in the NSSO survey. The amount of kerosene for lighting was then estimated from the consumption patterns of households that use kerosene primarily only for lighting. The kerosene use for backup lighting was similarly estimated from households not using kerosene primarily either for cooking or lighting. For defining the electricity consumption for lighting, the regression equations from Letschert and McNeil (2007) between the number of electric light points and expenditure, was used. The resulting shares of useful energy from different energy sources are depicted in Fig. 3.

3. The problem of consumer energy choice

In classical demand theory the problem of consumer choice is usually described as a problem of utility maximization under a budget limit, with a utility function characterizing the consumer's preferences for consuming varying amounts of different types of commodities. As for energy consumption, a consumer benefits from a higher level of useful energy consumption and is likely to prefer more convenient energy forms over inconvenient ones.

In the context of developing countries, the poor households—having a more limited budget for energy consumption—are forced to choose the more inconvenient but less costly alternative as otherwise they would trade off adequate energy consumption levels for convenience. The inconvenience—comprising intangible factors such as higher time consumption and exposure to particulate matter—carries a non-monetary burden or *an inconvenience cost* for the household and is an essential element in the choice problem.

Let us assume that the consumption of energy can be separated from other consumption to its own consumption problem, i.e. that the utility from energy is separable from other sources of utility and that the consumer has a specific energy budget. If the problem is first simplified to only distinguish a single modern, convenient fuel and a single traditional, inconvenient one, the energy consumption problem is

$$\max_{E_t,E_m} \quad U(\eta_t E_t + \eta_m E_m) - \varphi(E_t)$$
$$\text{s.t.} \quad p^T E = B, \tag{1}$$

where E_t and E_m are the consumption levels of traditional and modern fuels, U the utility from energy consumption, η_t and η_m the conversion efficiency for E_t and E_m, φ disutility from consuming the inconvenient fuel, p the price vector for E_t and E_m and B the budget limit.

If the preferences are locally non-satiable and the utility function is continuous, a problem of minimizing costs to yield the amount of utility equaling the solution of (1) arrives at the same consumption choice and thus is an alternative formulation to the consumer choice problem (Mas-Colell et al., 1995). For this particular problem, the cost minimization problem can be reformulated by introducing a cost on the consumption of traditional fuels instead of using the disutility function φ. In this problem setting the required utility level is then that of the fuel consumption, $U(\eta^T E^*)$, where E^* is the solution vector for the utility maximization problem. With a strictly increasing utility function U, the required utility can written purely in the form of useful energy. Thus an equivalent problem for (1) is a cost minimization problem

$$\min_{E_t,E_m} \quad p^T E + c(E_t)$$
$$\text{s.t.} \quad \eta^T E = \eta^T E^*, \tag{2}$$

where c is the inconvenience cost with $c>0$ and $c'>0$, η the efficiency factor vector for traditional and modern energy, and E^* the solution for (1), which can be obtained in practice from energy consumption statistics.

The situation can also be described graphically, as is done in Fig. 4. The solid lines describe the original utility maximization problem with the optimal solution lying in the point where the budget line $p^T E$ touches the curve of constant utility $U(\eta^T E^*) - \varphi(E_t^*)$. The same solution E^* is acquired from the cost minimization problem, presented with dashed lines, at the point where the cost curve $p^T E + c(E_t)$ touches the useful energy line $\eta^T E$.

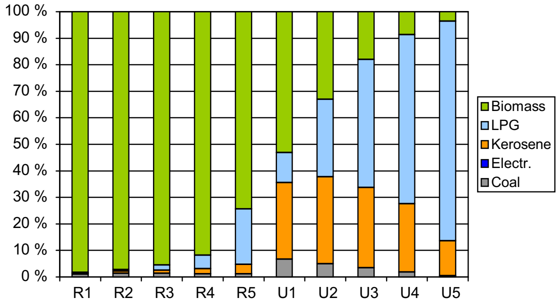

Fig. 3. The share of different energy forms in household useful cooking energy consumption for rural and urban expenditure quintiles.

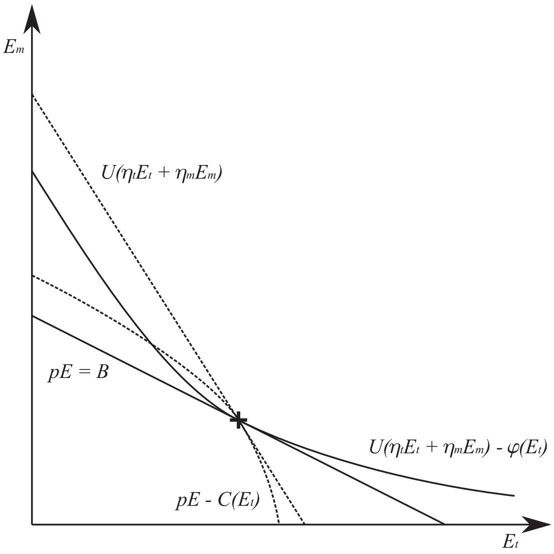

Fig. 4. The consumer energy choice problem, formulated as an utility maximization (solid lines) and cost minimization (dashed lines) problems. Both yield the same solution, marked with a cross.

This formulation yet lacks an explicit form for the inconvenience cost function $c(E_t)$. Regarding the energy choice problem, however, we are mainly interested in the marginal inconvenience cost $c'(E_t)$. The first order optimality conditions of (2) require that in the optimum

$$\frac{c'(E_t)}{\eta_t} = \frac{p_m}{\eta_m} - \frac{p_t}{\eta_t}, \tag{3}$$

that is, the marginal inconvenience cost in terms of useful energy equals the difference in the price of useful modern and traditional energy.

In the attempt to construct a linear energy choice model based on cost minimizing behaviour, further assumptions on the functional form of $c'(E_t)$ in (3) will be made in Section 4.3. A linearized version of the cost minimization problem (2) differs only from the original, non-linear model in that the inconvenience cost $c(E_t)$ is linear $C \cdot E_t$, and in practice the problem consists of simply selecting the technology with lowest costs per useful energy output.

4. Determinants of fuel choice

Section 3 outlined a basic theoretical framework for analyzing the energy choice problem. The presented framework is very generic and employable to a large number of consumer energy choice settings. In constructing a choice model for Indian households, a number of complementary, practical considerations have to be taken into account.

The most obvious determinants, prices and technological parameters of fuels and appliances, have to be supplemented with assumptions on how different consumers value costs and savings in different points of time, i.e. how costs are discounted, and how their preferences should be represented through the inconvenience cost. It is also important to assess whether there are additional constraints—such as the availability of biomass—that should be taken into account in the model.

4.1. Prices and technological parameters

The costs and efficiencies of different energy technologies are both explicit in the cost minimization problem (2). The total cost comprises the fuel cost and appliance cost, compared across the technology options by either the net present value (NPV) or annualized costs per useful energy of each technology, using an appropriate discount rate. Each technology is thus characterized by its investment cost per unit energy consumption, efficiency (η) and appliance lifetime.

The average fuel costs, estimated from the NSSO survey data, are presented in Table 1. From the original fuel division, firewood, dung and charcoal have been aggregated into "Biomass", and coal and coke into "Coal". Apart from a slight income bias, the average prices were relatively homogeneous across the consumer groups. The groups' stated prices varied less than 10% around the average, indicating that the average price estimates should be relatively reliable. The average price of firewood and electricity was higher among the urban population, which was interpreted as an actual difference in the prices between urban and rural areas. PDS kerosene denotes subsidized kerosene distributed through the public distribution system (PDS).

Table 1
Average fuel prices (Rs/GJ)[a] as implied by the NSSO survey.

	Rural	Urban
Coal	85	85
Electricity	373	415
Kerosene	282	282
PDS kerosene	112	112
LPG	270	270
Biomass	62	80

[a] Market exchange rate: 42 Rs(2000) = 1 USD(2000).Purchasing power parity: 13.7 Rs(2000) = 1 USD(2000) (IMF, 2008).

Numerous studies have cited different technological parameter sets for the appliances, e.g. Reddy (2003), Masera et al. (2000), Pachauri (2004b) or TERI (2006). The parameters used in this study are based on Reddy (2003), except the efficiencies of biomass and kerosene cookers, which were 5 percentage points higher than in Reddy (2003) and set at the values reported in Masera et al. (2000), Pachauri (2004b) and TERI (2006). The parameters used are presented in Table 2.

Table 2
Parameters for household cooking technologies.

	Efficiency (%)	Inv. cost	Life (a)
Cooking			
Biomass	15	1.5	5
Coal	15	1.5	5
Kerosene	40	15	7
LPG	60	267	15
Electric	75	833	15

Investment costs are in terms of Rs/GJ input energy.

4.2. Discount rates

Energy investments, in general, include an upfront investment cost and fuel costs distributed over the lifetime of the appliance. The common solution to this temporal distribution of costs is the calculation of net present values by discounting future costs with the so-called social planner's discount rate or risk-free interest rate, both often around 5%. An implicit assumption behind this is that there are financing opportunities present with the chosen discount rate and thus cash reserves do not constrain the investment. While this is often true for institutional investors, such opportunities are not always present for households, especially for low-income rural households. Even if the financing would be available for these consumers, the interest rates can be high or borrowing can carry a transaction cost, impeding the efficient use of the financing opportunity.

This lack of funding may result in a scarcity of cash within the budgeting period of the household, which can be considerably shorter for poor households with no savings as compared to more affluent ones. Thus a poor household has to either save in advance for the investment, or to reduce other consumption within the budgeting period when the investment is made. In the former case the net present value of the investment at the time the investment is made is higher than the actual investment cost, as the savings have been made in advance. The latter case might not even permit the investment, as the investment cost might be prohibitively large (Leach, 1992; Gangopadhyay et al., 2005). Even if possible, with a decreasing marginal utility from consumption the disutility from a large investment is greater than the increased utility from smaller savings in the future, deterring the investment.

These facets of the intertemporal choice problem can be incorporated through employing a higher discount rate than the social planner's discount rate in the analysis. Furthermore, the discount rate should be higher for consumers with lower income, for whom cash is even scarcer. This has been already noted by Reddy and Reddy (1994) for Indian households.

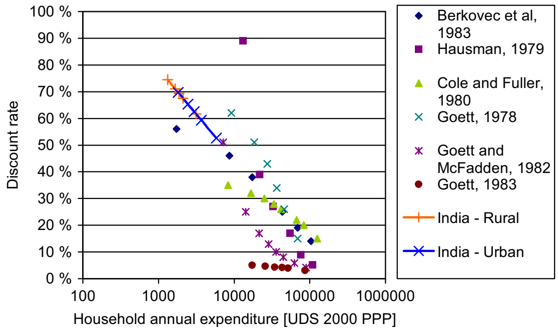

Fig. 5. Empirical implicit discount rates (IDRs) for energy appliances from various studies as a function of household income (in USD_{2000} PPP per household), as reviewed by Train (1985), with estimated IDRs for 10 Indian consumer groups used in this study.

Table 3
The average annual household expenditure (in USD_{2000} PPP) and fitted discount rates for the 10 consumer groups used in this study.

Quintile (%)	Rural		Urban	
	Expend.	DR (%)	Expend.	DR (%)
0–20	1319	74	1818	70
20–40	1661	71	2455	65
40–60	1865	69	2972	62
60–80	2111	68	3681	59
80–100	3133	62	5806	53

A vast number of studies have attempted to quantify consumer's discount rates, giving extremely diverging results. For example a review on a large number of discounting studies by Frederick et al. (2002) cites results ranging from negative to infinity. However, if confined only to results from real field studies, as distinct from hypothetical and experimental studies, the range narrows to between 0% and 300%. Even though the review did mention that the relationship between income and discount rates has been observed in a number of studies, it did not cite any explicit income-discount rate correspondence.

This lack is remedied by an older review of 14 studies on different energy-related investments by Train (1985), which also confirms the assumption that consumers with higher income use lower discount rates in their decisions. Selecting the studies on household energy choices from this review provides a good reference point for the energy choice model developed in this paper.

For making the findings reviewed by Train (1985) comparable to the expenditure levels reported for Indian households, the income levels from the six selected studies were compounded to USD_{2000} (IMF, 2008), to which the Indian households' expenditures—reported in national currency units in the survey—were also converted by using purchasing-power-parity (PPP) indices from IMF (2008).[1] The data from Train (1985) and estimates for the 10 consumer groups, corresponding to a logarithmic curve fitted to the empirical data, are depicted in Fig. 5, with the consumer groups' estimated rates being also explicitly presented in Table 3.

The discount rates in Table 3 are remarkably higher than the 5% rate usually used in such studies, and gives considerable weight to the up-front costs associated with purchasing stoves. For comparison, Reddy and Reddy (1994) have also estimated discount rates for households in Bangalore, based on the actual decisions that these households made regarding their fuels choices. With the assumption that the households switch fuels types if the internal rate of return associated with the switching is above their own discount rate, the authors associated the shift from firewood to kerosene to a discount rate of around 200%, and from kerosene to LPG to a rate around 10%. Compared to these estimates, the rates in Table 3 seem relatively moderate in the case of switching from firewood to kerosene, but too high for a shift from kerosene to LPG. However, the IRR estimates by Reddy and Reddy (1994) are obviously very dependent on the parameters employed, which were not presented in their paper. Still, their paper provides additional evidence that Indian consumers are likely to use high rates for discounting.

4.3. *Inconvenience costs*

A basic formula for the marginal inconvenience cost was given in Eq. (3) as the relation between the optimal amount of traditional fuel consumption and the difference in marginal useful energy costs between the two fuels. For the fuel choice model, a single inconvenience cost reproducing consumers' real life choices is, however, needed. In other words, it is required that the model would select the main cooking fuel, implied by the statistics, as the fuel of choice with each consumer group. In addition, if the effect of changes in fuel prices—e.g. fuel subsidies—is to be modelled correctly, the inconvenience cost estimates should provide a trigger of the right magnitude for switching the choice of main fuel.

If an additional assumption to (3) is made that the marginal inconvenience cost $c'(E_t)$ is linear, i.e. $c'(E_t)=\alpha\cdot E_t$, then the marginal inconvenience cost of satisfying the cooking energy demand fully with biomass would be

$$c'\left(\frac{\eta^T E^*}{\eta_t}\right)=\left(\frac{\eta^T E^*}{\eta_t E_t^*}\right)\left(\frac{\eta_t}{\eta_m}p_m-p_t\right). \qquad (4)$$

This can be reformulated as

$$C_{full}=\left(\frac{\eta_t}{\eta_m}p_m-p_t\right)+\frac{p^T E^*-p_t\eta^T E^*\eta_t^{-1}}{E_t^*}, \qquad (5)$$

which gives the inconvenience cost for full biomass consumption as a sum of the marginal cost difference and the price premium that the consumers have paid for their actual consumption.

However, using Eq. (5) to estimate the inconvenience cost would result in the traditional fuel, by definition, always being more costly than the modern one, as the inconvenience cost would exceed the marginal cost difference. Instead, an average marginal cost

$$C_{avg}=\frac{1}{2}\left(\left(\frac{\eta_t}{\eta_m}p_m-p_t\right)+\frac{p^T E^*-p_t\eta^T E^*\eta_t^{-1}}{E_t^*}\right) \qquad (6)$$

would have the desired characteristics described above. This is illustrated in Fig. 6, which portrays a consumer using biomass as the primary fuel with useful traditional energy consumption of $\eta_t E_t^*$. As can be seen from the figure, the marginal cost difference $\eta_t/\eta_m p_m-p_t$ exceeds the average inconvenience cost C_{avg}, and the linear choice model would select the traditional fuel as the fuel of choice for this consumer. Also, if the price of the modern fuel would be lowered so that the marginal cost difference would be below C_{avg}, the consumer would choose the modern fuel as the

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[1] The PPP rate might differ between consumers with different consumption patterns. Income-specific PPP rates could also incorporated in the conversion, but as according to Asian Development Bank (2008) the differences in PPP rates for Indian consumers with different income levels are only minor, a single PPP rate from IMF (2008) was used for simplicity.

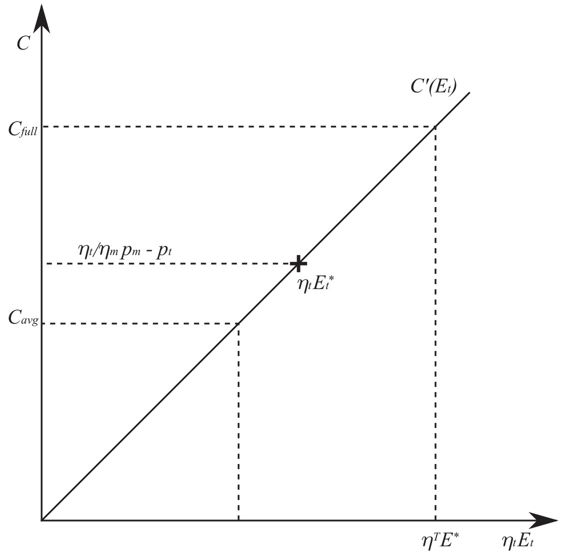

Fig. 6. An example with a linear marginal inconvenience cost curve $c'(E_t)$. The marginal cost difference $\eta_t/\eta_m p_m - p_t$ is above C_{avg}, and thus the consumer is using the traditional fuel, i.e. biomass, as its main fuel source.

Table 4
Inconvenience costs (Rs/GJ) for biomass, calculated with (6), for the rural and urban consumer groups.

Quintile (%)	Rural	Urban
0–20	23.8	27
20–40	24.0	43
40–60	24.4	76
60–80	25.4	149
80–100	30.0	310

main choice, which would also be the result from the use of the linear choice model.

The average inconvenience costs for the consumer groups considered were calculated from Eq. (6), using the minimum of either the price of kerosene or LPG—inclusive of the associated annualized investment cost—as the reference modern fuel price. The results are presented in Table 4. As can be seen from Table 4, the inconvenience cost is increasing with income within both rural and urban populations.

There is no good reference point in the literature for the inconvenience cost values, although, e.g. Reddy and Reddy (1994) have noted the importance of inconvenience in the fuel choice problem. van Ruijven (2008) made an effort to estimate these costs but their method yielded counterintuitive results. However, as van Ruijven (2008) noted, the limited availability of LPG in rural areas might affect the inconvenience cost estimates, and inconvenience costs for rural consumers might be higher in the absence of these availability barriers. When compared to the actual price for biomass, estimated as 62 Rs/GJ in rural and 80 Rs/GJ in urban areas, the estimated inconvenience costs are quite moderate for the entire rural population, less than 50% of the fuel price. For the urban population the inconvenience cost estimates rise sharply with income, almost reaching the actual price of biomass already for the third quintile group.

An interpretation for the observed behaviour of the inconvenience costs can be based on the factors behind the inconvenience. As has been already mentioned, a higher time spent and exposure to particulate matter is associated with the use of traditional fuels. The low income levels of poor households and more limited work opportunities of the rural population—especially with women, who usually gather and use the firewood—involve lower opportunity cost for time (Pachauri, 2004b), and consequently lower inconvenience costs for low-income and rural households. Also, lack of information on the adverse effects of particulate matter among the less educated, lower income households might be an additional explanation. Cultural preferences and traditions have also been reported by Masera et al. (2000) as factors affecting household energy choices. With less empowered women gathering and using the fuels and men making the decision of which fuel to use—a situation more likely to be the case for rural populations—there might be a tendency to undervalue the inconveniences (Cabraal et al., 2005).

4.4. Other determinants

4.4.1. Time consumption and availability of biomass

The time needed to gather a certain amount of fuel might be a constraining factor for consumers, and depends on available biomass resources. A study by Bhagavan and Giriappa (1995) on time used for gathering traditional fuels in eight villages in three different climatic environments in India, estimated the average pace for gathering traditional fuels at the community level as varying from 38 MJ/h in the semi-arid regions to 62 MJ/h in the tropical regions. A pace of 50 MJ/h would equate to roughly as 3.5 kg of firewood per hour. Assuming this gathering pace, the average biomass consumption of the rural population implied by the NSSO survey, 3600 MJ/a/capita, would require 12 min per day per capita to gather the fuel. Based on this estimate, the time budget requirements needed appear unlikely to be a constraining factor for the population as a whole.

As was noted already in Fig. 2, traditional fuels are also traded. This has two important implications. First, due to the possibility of purchasing some of the fuel, time does not constrain the consumption of traditional fuels on the level of individual consumers, but only possibly at an aggregate level. At this level, based on the calculation above, only a fraction of the workforce appears to be required to gather the fuel and thus time consumption does not seem to be a major constraining factor even at the aggregate level. Second, using freely gathered traditional fuels also carries a monetary opportunity cost due to the presence of the market for traditional fuels. Therefore the monetary value or price of the fuel is also significant for those who collect their own fuel, and should reflect the time needed for gathering the fuel.

4.4.2. Budget

In the preference maximizing choice model, presented in Eq. (1), the budget limit characterizes the solution with the preferences of consumers. In the equivalent cost-minimizing problem of Eq. (2), the budget constraint is met through the cost minimization. This, however, holds in general only when prices are stable, and if changes in (real) prices are assumed, the budget constraint would have to be considered also in the cost-minimizing problem.

The constraining feature of the budget, however, increases only with increasing prices, assuming that the own-price elasticity of aggregate energy consumption is above -1, i.e. the demand is relatively inelastic. This is an appropriate assumption as there are no close substitutes for energy consumption. Gundimeda and Köhlin (2008) also reported that the Hicksian (compensated) own-price elasticities estimated from the NSSO data for different fuels were generally between -0.1 and -0.7.

This study assesses the effect of reduced energy prices due to fuel subsidies, and the resultant potential shift from traditional fuels to modern fuels. A fuel subsidy, based on the reasoning above, then leads to a reduced importance of the fuel budget constraint. Also, the higher efficiency of LPG and kerosene stoves compared to those used with traditional fuels balances out their higher fuel price, either partially or wholly, thus also reducing the effect of the budget constraint. Although the fuel budget constraint was implemented in the MESSAGE-Access model, described in Section 6, the factors mentioned above rendered the constraints mostly non-binding.

4.5. *The results from the choice model*

A household energy choice model based on the characteristics described above compares the annualized costs of different fuels, taking fuel, investment and inconvenience costs into account, and using the discount rates presented in Fig. 5 individually for each consumer group. The model results in all rural consumers choosing biomass; and among urban population U1 choosing biomass, U2 choosing kerosene and groups U3–U5 choosing LPG. Comparing these results to Fig. 3 reveals that the choices correspond exactly to the main cooking fuels the groups use, suggesting that the model is able to reproduce actual household choices regarding the main cooking energy forms.

It should be borne in mind, however, that the linear cost optimization approach intends to solve the energy choice problem with a single solution, whereas in reality many households in India use multiple fuels for cooking. Therefore the results from the choice model might be slightly unbalanced, and might not portray the whole spectrum of energy forms used, although on the level of the total population the actual energy mix is more accurately represented.

5. Sensitivity analysis of the choice model

The parameters in the choice setting can be divided into technical and price parameters, on which we have relatively good estimates, and more speculative parameters, namely the discount rates and inconvenience costs. Following this division, the sensitivity analysis of the fuel choice model is also divided into two parts.

Given the prices and technology parameters presented in Tables 1 and 2, the choice problem involves choosing a single technology with lowest annualized costs per useful energy implied by the discount rate, and inclusive of the inconvenience cost for biomass. The solution itself therefore gives no indication of how close the costs of other technologies are to the optimal one.

The problem can, however, be expressed as a phase diagram on a discount rate–inconvenience cost plane, explicitly illustrating the proximity of other technologies to the optimal. This is represented in Fig. 7, separately for rural and urban consumers to account for the differences in fuel prices, along with the point estimates of discount rates and inconvenience costs for each consumer group.

As can be seen from the figure, all of the rural consumer groups are well inside the biomass phase, but approach the LPG phase with higher income. Therefore, the rural consumers' choices are not sensitive to their discount rate and inconvenience cost parameters. The urban consumer groups are scattered on all three phases, with the lowest income group in the biomass phase, U2 in the kerosene phase and three groups with the highest income in the LPG phase. As many of the estimated parameter pairs lie close to the phase boundaries, the model results for the urban consumers appear to be clearly more sensitive to the parameter values than for the rural population.

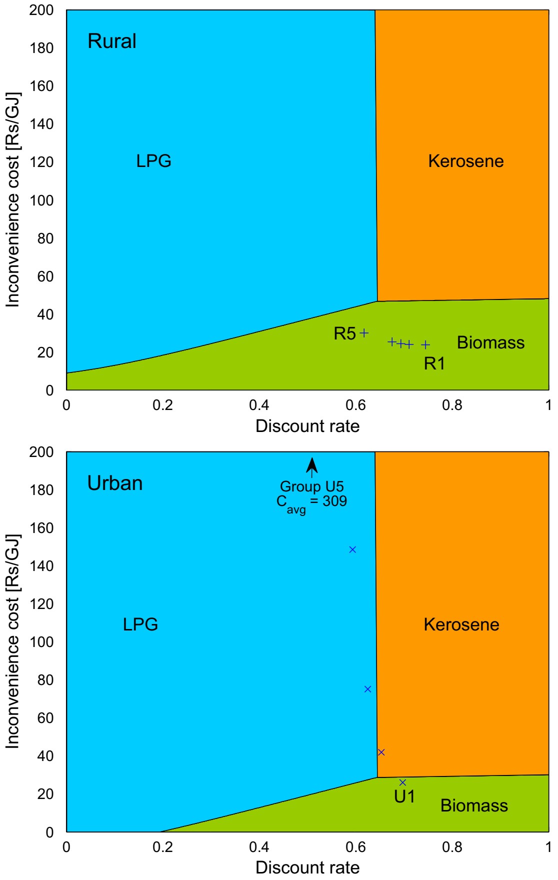

Fig. 7. Phase diagrams for the cost minimization problem in terms of different implicit discount rates (*x*-axis) and inconvenience cost levels (*y*-axis). The phase diagram differs slightly between the rural (top) and urban (bottom) consumers due to fuel price differences. The estimated IDRs and inconvenience costs of the different consumer groups are presented with crosses.

However, as both the actual values and consumer preferences and technological parameters might vary, there is not a single cost-optimal technological choice to the problem at hand or the consumer might be unable to identify it, and therefore the aggregate choice will be a mix of fuels that are close to the optimum. Then, if we broaden our view away from the decision of selecting a single cost-optimal fuel, the results from the phase diagram compare well with Fig. 3 as the proximity of a group's parameters to different fuel phases correlate with the each group's main energy form for cooking implied by the statistics. The rural consumers use predominantly biomass, but the highest quintile also uses LPG to some extent. The lowest urban expenditure quintile uses mostly biomass, but also some kerosene, the second lowest quintile uses approximately equal amounts of kerosene, biomass and LPG. For the three highest expenditure groups the share of biomass declines steeply and the share of LPG rises, reaching over 80% for the highest group.

Although the phase diagram seems to compare well to the observed statistical consumption patterns, the phase diagram is also dependent on the techno-economic parameters. These affect the location of the triple point, i.e. the intersection of the three fuel phases. The sensitivity to cost, efficiency and equipment lifetime estimates was assessed by deviating each parameter by ±5% and ±10% from the values stated in Tables 1 and 2. The results from this experimentation are presented in Fig. 8. The inconvenience costs also vary depending on the parameter values, and therefore instead of a single cross, a group of 12 crosses represents each consumer group in the figure.

It can be seen from Fig. 8 that the rural consumers are sufficiently deep in the biomass phase so that the results are resilient to changes in all parameters. The figure for urban consumers suggests that the model might not be entirely conclusive, as a 10% change in the price or efficiency of kerosene or LPG would shift the triple point sufficiently to induce a result different from that of Fig. 7.

Should the default parameter estimates be unbiased, however, there should be also no actual bias in the results of choice model. As there are, however, uncertainties and variance in both actual and perceived values of prices and technical parameters, this would add to the distribution of actual choices in reality around the optimum. It should also be noted that the different uncertainties counteract each other to some extent, reducing the sensitivity of the model to the parameter uncertainties as a whole. Therefore, even though the model is relatively sensitive to the parameters used, it should give a good indication of the determinants of fuel choice and what kind of an effect a change in these determinants might have on choices.

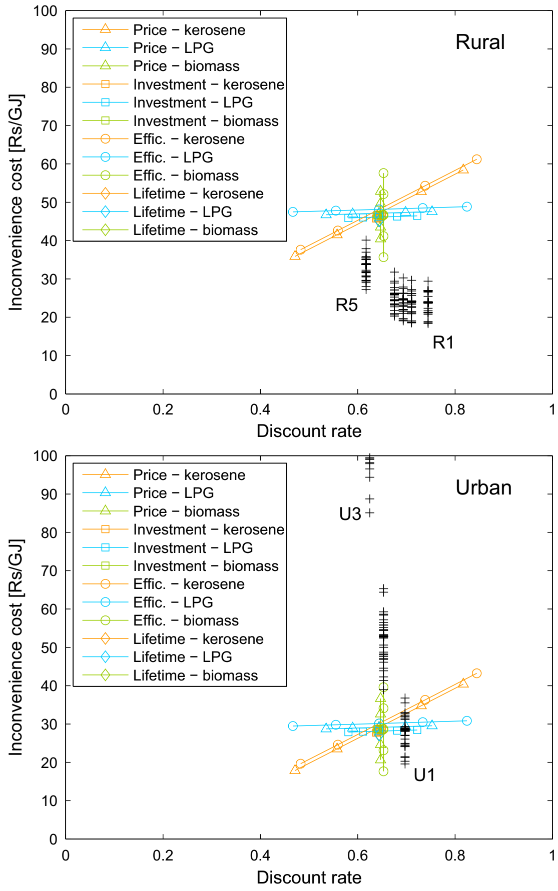

Fig. 8. Sensitivity of the triple point in Fig. 7 and inconvenience costs to different assumptions with ±5% and ±10% deviations in the fuel price, investment cost, efficiency and appliance lifetime parameters for rural (top) and urban (bottom) consumers. The lines are slightly displaced to improve visual distinguishability. The black groups of crosses depict the effect of different parameter assumptions to the inconvenience cost, calculated with (6).

6. Scenarios up to 2020

As an extension of the developed energy choice model, the choice framework was implemented in an Indian household-sector demand-side model, MESSAGE-Access, using the MESSAGE energy modelling system (Messner and Strubegger, 1995). The MESSAGE framework uses linear cost optimization as the solution concept for calculating long term energy scenarios, and the most notable implementation of the system is the global 11 region integrated assessment model (see e.g. Riahi et al., 2007). In addition to producing a baseline scenario for household energy consumption, the model was used to explore policy scenarios aiming to improve the market penetration of modern cooking fuels, especially among the rural poor.

The MESSAGE-Access implementation incorporates multiple consumer groups, each with distinct inconvenience costs and discount rates. The consumers were grouped into expenditure classes corresponding to the rural and urban expenditure quintiles of 2000. Therefore due to economic growth and increasing expenditure levels, households migrate gradually from the lower to the higher expenditure groups.

As an exception to the grouping, however, the highest rural group was split into two parts, R5-1 and R5-2, in a manner that the group R5-2 would have a sufficiently high expenditure for it to only barely prefer LPG to biomass according to the energy choice model. This configuration enables the model to account for the autonomous shift from traditional to modern fuels resulting from economic growth. The share of R5-2 of the rural population was, however, only 1.3% in 2000, which compares well with the NSSO statistics indicating that of the highest earning rural 5%, only 30% used LPG as their main cooking fuel in 1999/2000.

The inconvenience costs and discount rates for the groups R1–R4 and U1–U5 were taken, respectively, from Table 4 and Fig. 5. For R5-1 and R5-2 the inconvenience costs were 29.2 and 43.1 Rs/GJ, respectively, and the discount rates 62% and 59%.

The shift of expenditure distributions—for the rural and urban populations separately—were estimated by extrapolating the parameters of a lognormal curve fitted to the real expenditure distributions from NSSO survey data between 1993 and 2007 with consumer price inflation estimates from IMF (2008). The shares of consumer groups in the MESSAGE-Access model from the total rural and urban populations are presented in Fig. 9. The growth of the total urban and rural population sizes were taken from the B2 scenario by Riahi et al. (2007).

As the MESSAGE model framework, however, operates inherently on a single discount rate, the investment costs were multiplied with a factor representing the effect of a higher discount rate. This factor is the ratio between annualized investment costs for the appliance lifetime T with the model's discount rate r_M and the discount rate r_i of the consumer group i, i.e.

$$\frac{r_M^{-1}(1-e^{-r_M T})}{r_i^{-1}(1-e^{-r_i T})}. \qquad (7)$$

As the cost minimization problems with NPVs or annualized costs are equivalent, using multiplied investment costs and model discount rates yields the same outcome as would minimization with the consumer's own discount rate.

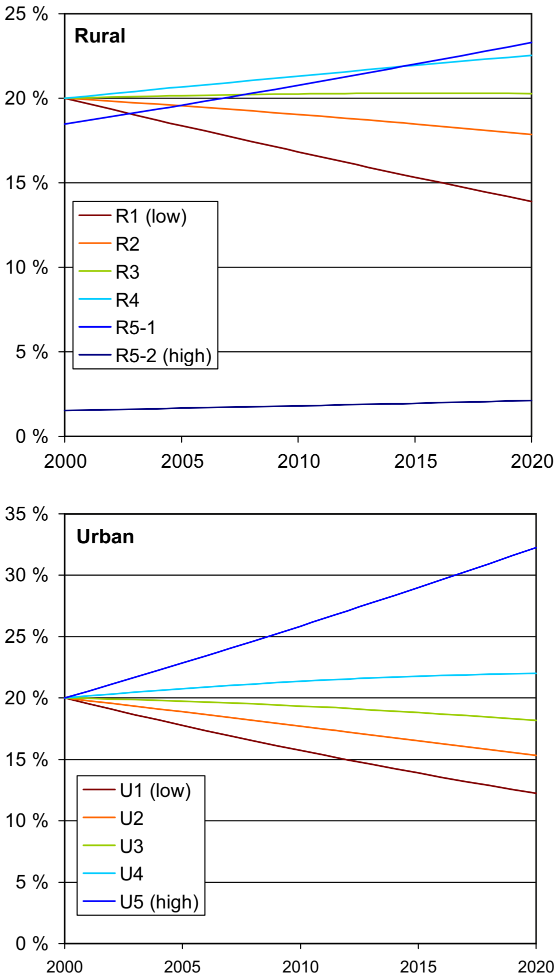

Fig. 9. The shares of the consumer groups within the total rural (top) and urban (bottom) populations up to 2020 in the scenarios.

6.1. Policy measures for improving the adoption modern fuels

Based on the determinants considered in Section 4, possible measures aiming at a larger penetration of modern cooking fuels should target either the costs, discount rates or the inconvenience costs. Of these three, lowering the costs through fuel subsidies and discount rates, e.g. through micro-financing opportunities, seem more plausible than aiming for policies that lower inconvenience costs, the sources of which are more ambiguous. Subsidizing the appliances is obviously also a possibility, but this might be hard to implement effectively in practice due to the heterogeneity of products available on the markets, and was thus not considered here. Also, the state-owned oil-companies and the PDS currently act as the distribution chain for subsidized LPG and kerosene (Gangopadhyay et al., 2005), which ease the implementation of applying fuel subsidies.

As the discount rate of the poor consumers was estimated to be dramatically larger than the usual assumption of the socially optimal rate, it could be argued that such high rates produce a socially sub-optimal outcome. Thus it would be beneficial to provide a funding scheme for appliance investments with interest rates closer to the social planner's discount rate. Based on Robinson (1996), micro-financial institutes, which provide loans for the poor in developing countries, generally charge interest rates of 20–35%. This range was used as a reference for discount rates in the improved financing scenarios by associating the high end to the R1 group and a 5% rate to the U5 group and interpolating for the groups in between based on their expenditure levels. The effect of providing improved financing opportunities was assessed both as the only policy measure, and in conjunction with a fuel subsidy.

With the assumed fuel subsidies, the price of LPG or kerosene was reduced by 20%, 33% or 50% from the real price of 2000 in the policy scenarios. For comparison, in 2000 the price of PDS kerosene was roughly only 40% of the market price, but the quantity of PDS kerosene supplied was limited. Thus, especially in the high subsidy scenarios, this may be seen as quite an extreme measure. All of the measures were assumed to be announced in 2010 and to be implemented from 2011 on, so that the household energy scenarios would follow the baseline scenario up to 2009, after which the households could react to the announced policies.

6.2. Results

The baseline scenario for cooking energy consumption, illustrated in Fig. 10, follows closely the results of the basic fuel choice model. Among the rural population, biomass is clearly the fuel of choice for all consumer groups except R5-2, although it is supplemented with the limited supplies of PDS kerosene. Existing LPG stoves are also used for their lifetime, but not replaced. For the urban population, U1 selects biomass, U2 kerosene, and the higher expenditure groups LPG. Similar findings—i.e. the dominating status of biomass in rural areas and an increasing share of LPG in urban areas—in projections up to 2010 have also been made by Reddy (2003).

In the figure, the year 2000 corresponds to the statistical values from NSSO data, and the actual results from the MESSAGE-Access model start from year 2001. As can be seen, the model reproduces the statistical consumption patterns with reasonable accuracy, especially when measured in useful energy terms and taking the uncertainties in the biomass consumption figures into account. Also, as was noted in Section 4.5, the choice model represents only the main fuels used by households, and therefore any secondary cooking energy forms are not represented in the scenarios.

In the baseline scenario with no policy changes, the rural population will continue to use traditional biomass as its main cooking fuel. With the growing rural population, this leads to an increase in the absolute number of people affected by the adverse effects of traditional fuel consumption, e.g. particulate matter exposure. Also, as the energy consumption is likely to rise due to income growth, the consumption of firewood increases even more than the rise in population size, resulting in possibly greater deforestation and forest degradation, as already the current firewood consumption is estimated to be at an unsustainable level (Kaul et al., 2009).

The effect of the policy measures was very straightforward in most cases. Without improved financing possibilities, a partial market penetration of modern fuels occurs within the rural population with a 20% kerosene or 33% LPG subsidy, and a full penetration with subsidies of 33% and 50%, respectively. At the same time, even the low 20% subsidy on LPG prompts the U2 group to switch to LPG, and the 20% kerosene subsidy encourages kerosene consumption so that it gradually becomes the main cooking fuel in urban areas.

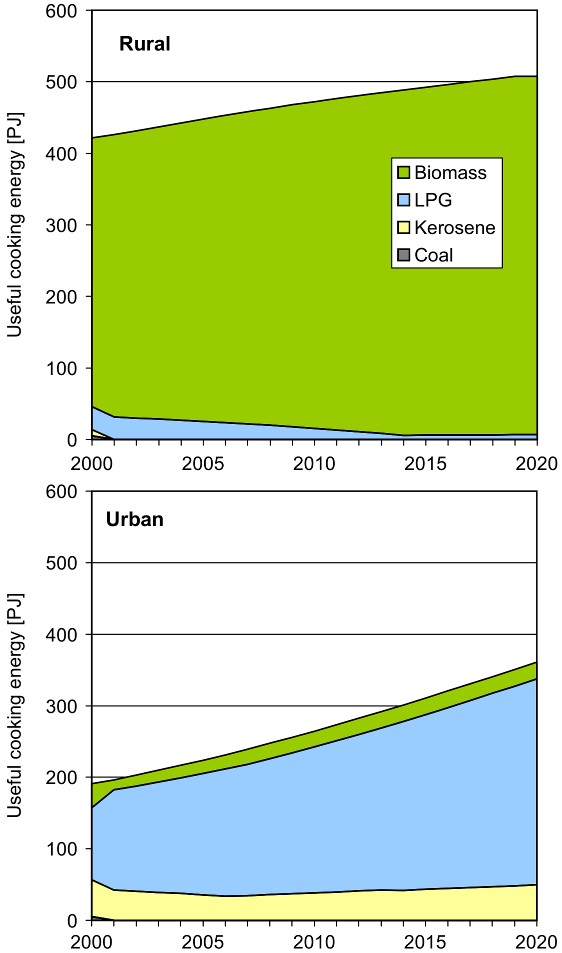

Fig. 10. Baseline scenario for household cooking useful energy consumption (PJ) for the rural (top) and urban (bottom) populations. Year 2000 corresponds to statistical values and the results from the model start from 2001.

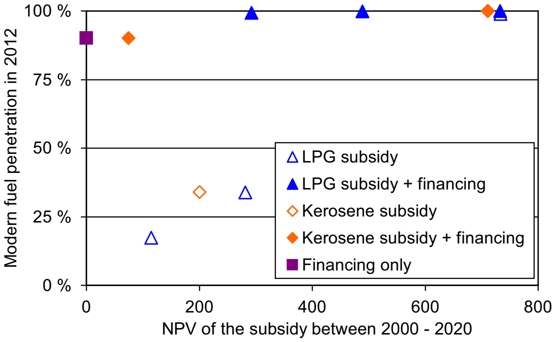

Fig. 11. The market penetration of modern cooking fuels in 2012 (*y*-axis) in rural areas with different policies compared to the net present cost [Bn. Rs(2000)] of up to 2020.

Improved financing, in the absence of any additional subsidies, would already cause groups U1 and U3–U5 to switch to LPG as their main fuel. This can also be seen from Fig. 7 by shifting the discount rates of the points to levels below 35%. If this policy is combined with a 20% LPG subsidy, LPG is adopted by the whole population, apart from some groups also using the PDS kerosene in its full availability. Financing, however, does not notably improve the effect of kerosene subsidies, due to the relatively low investment cost of kerosene stoves.

For evaluating the effectiveness of the policies, the net present cost of the policies up to 2020 was calculated to be compared with the market penetration of modern cooking fuels in rural areas in 2012. For the cost calculations, the cost of microfinancing was estimated to be zero, as micro-finance companies cover their activity costs from the interests charged, and can actually even profit from their activities.

The cost-effectiveness of policies is portrayed in Fig. 11. In choosing the pareto-optimal policy with high penetration and low costs, three points emerge: financing only or financing combined with a 20% subsidy on either LPG or kerosene. Of these three, the kerosene option, however, results in only marginally larger penetration levels than in the scenario with only financing measures, whereas the LPG subsidy affects even the poorest consumers. To achieve this with kerosene subsidies, the cost rises rapidly and exceeds that of the 20% LPG subsidy. It should also be noted that this rapid change in the penetration and cost of the kerosene subsidy also produces a source of risk, should the subsidy level be set either too low or too high, as the actual response from the consumers might deviate from that implied by the model.

7. Summary and conclusions

Improving the prospects for modern energy use is an important prerequisite for improving the conditions of poor households in developing countries. In particular, providing access to modern cooking fuels to such populations would reduce their exposure to harmful particulate matter, save their time for use in more productive activities and mitigate deforestation. Drawing from both the preference and budget constraint approach of classical demand theory and the cost-minimizing solution concept of various energy system models, a fuel choice model was developed in this work, using costs and technical characteristics of appliances and fuels, and discount rates and preferences in the form of inconvenience costs as key determinants. The determinants were specified separately for consumer groups instead of for the population as a whole, differentiating—based on Pachauri (2004a)—between different expenditure levels and whether the households live in rural or urban surroundings.

The fuel choice framework was then implemented as the MESSAGE-Access energy system model for India, which is planned to be integrated with the global MESSAGE model (Riahi et al., 2007) in future work. The novel elements of the model include differentiation of consumer groups, income specific discount rates and the accounting of preferences in the cost minimization framework through the estimation of inconvenience costs associated with traditional fuels. The fuel choice model developed in this work, was able to reproduce the main cooking fuel choices of all consumer groups, as implied by NSSO statistics. As an application, the MESSAGE-Access model was also used for evaluating the implications of policy measures such as fuel subsidies and improved financing in order to promote the adoption of modern cooking fuels in rural India.

Acknowledging the heterogeneity of consumers is a step forward to a more realistic representation of the household sector in energy system models. In existing linear cost-minimizing models a single energy form is usually used for a given purpose, and a sudden shift to a different one can result from small changes in the underlying parameter values. By differentiating among different consumer groups, even though a single consumer group's decision will still be sensitive to the input values, the aggregate consumption estimates are likely to be more robust and can reproduce a more realistic spectrum of different energy choices.

The actual determinants that distinguish consumer groups from each other in this work were differing fuel costs, discount rates and preference-related inconvenience costs. The prohibitively high investment costs of kerosene and LPG stoves for low income households has already been highlighted in previous literature e.g. by Reddy and Reddy (1994). Gangopadhyay et al. (2005) also noted that the price of a LPG cylinder might also be too high for the poor, though it might result in cost savings for them in the longer term. As income dependent discount rates were employed in this work considerably high discount rates, especially for the lowest income households were used that provided a more realistic estimate of the investment constraints for such households.

The estimation of the inconvenience costs associated with traditional fuels was another novel feature of this analysis. Numerical estimates for these preferences are scarce in the literature. An attempt was made by van Ruijven (2008) but they arrived at a rather counterintuitive outcome, with LPG and kerosene having a higher inconvenience penalty than traditional fuels. The inconvenience cost estimation procedure derived in this paper provided estimates that were higher for households in urban areas and rose with the income of the household. This seems a more intuitive outcome, given the lower opportunity cost of time and limited work opportunities for rural poor households, especially for women.

The model framework taking into account the heterogeneity of households, discount rates and inconvenience costs is of generic nature, and is applicable also for other countries and settings. Case-specific factors—such as prices of different energy forms and appliances, preferences, and expenditure distributions—obviously affect the actual numerical results and responses to different policies. However, the results on consumers' tendency to disregard energy efficient options with high up-front costs due to the high rates used discounting can be deemed indicative also for other settings.

A sensitivity analysis for the choice model suggested that there are often multiple fuels in close proximity of the cost optimum, but this proximity correlated well with the share of the fuels in the consumption mix of each consumer group. This is also compatible with the findings of Masera et al. (2000), that the households often use multiple energy sources instead of a single one.

A baseline scenario calculated with the MESSAGE-Access model resulted in an approximate continuation of the current consumption patterns. In this scenario, the number of people using traditional biomass in 2020 would rise by almost 100 million compared to the level in 2000. The policy scenarios with either improved financing opportunities, fuel subsidies or a combination of both, suggested that a major obstacle for the adoption of modern fuels, especially LPG, is the high investment cost and the discount rates that the consumers use in their energy related decisions. According to the results, subsidies alone may be inefficient for promoting modern fuels, as the steep up front investment costs are not affected. Improved financing opportunities for the appliance investment alone would already increase the penetration of modern fuels remarkably within the rural population. Combined with a small LPG subsidy, the whole population might be prompted to switch to LPG. With a kerosene subsidy, the effect of improved financing would not be as significant, and a subsidy level sufficient enough to affect choices for those with a very low income level might even induce consumers with higher incomes to shift from LPG to kerosene, raising the cost of the subsidy.

Gangopadhyay et al. (2005) have argued that the current LPG fuel subsidy in India is inefficient, as it benefits the rich more than the poor. However, if the heavy burden of up-front investment costs for the poor is eased through financing, the situation changes as the running costs of LPG are lower than of kerosene due to its higher efficiency. In addition, as Gangopadhyay et al. (2005) also observed, the kerosene subsidy is expensive, as a large share of the kerosene is illegally diverted away from the public distribution system.

At a time when the world is shifting to a low-carbon economy, it might sound odd to promote the adoption of fossil fuels. However, the additional emissions from using LPG in cooking for the entire population of India in 2020 would be only around 50 Mt CO_2, which is negligible when compared, e.g. to the 2200 Mt CO_2-equivalent estimate of total Indian emissions for 2005. The shift from cooking with traditional fuels to modern fuels will have a substantial effect on the lives of over 700 million inhabitants in 2020, and is likely to be an important precondition for the eradication of poverty among these households.

Obviously the model developed in this paper, although an improvement on previous modelling efforts, is not a full description of reality, and a number of caveats should be considered. First, fuel consumption is also a matter of physical access to the modern fuels, not only consumer choice. But then again, if the household's determinants of fuel choice do not imply a switch to modern fuels, improving the access to these fuels will not increase their adoption to its full potential. Second, the supply of biomass was assumed to be at a constant cost or opportunity cost in this work, whereas in reality the potential supply of biomass varies considerably between regions and therefore costs to may vary. Third, in the policy scenarios, the model did not include any own-price elasticity of demand, and the applied subsidies did not therefore affect the total cooking energy demand. The subsidy might in fact increase the fuel consumption and raise the cost of the scheme. Despite these caveats, the overall results from the model are robust, and unlikely to be affected even if these issues were taken into account in more detail.

One may also argue that subsidies are a fiscally unsustainable way of promoting the shift to cleaner fuels, and a strain on government budgets. The case might actually be to the contrary in the longer term, for the subsidy could increase labour productivity, as the time used for gathering and using firewood could be used more profitably. By nourishing economic development among the rural poor, this would also increase the opportunity cost of time—and through this effect, shift the price balance permanently in favour of modern fuels. Therefore the subsidies can be seen as a transitional necessity. Thus, as a conclusion, economic development and the adoption of modern cooking fuels are very likely to go hand in hand and it is hard to imagine improving one without improving the other.

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References

Asian Development Bank, 2008. Research Study on Poverty-Specific Purchasing Power Parities for Selected Countries in Asia and the Pacific. Asian Development Bank, Manila, Philippines.

Bhagavan, M., Giriappa, S., 1995. Biomass, energy and economic and natural resource differentiation in rural southern India. Biomass and Bioenergy 8, 181–190.

Bhattacharyya, S., 2006. Energy access problem of the poor in India: is rural electrification a remedy? Energy Policy 34 3387–3397.

Cabraal, R.A., Barnes, D.F., Agarwal, S.G., 2005. Productive uses of energy for rural development. Annual Review of Environment and Resources 30, 117–144.

Farsi, M., Filippini, M., Pachauri, S., 2007. Fuel choices in urban Indian households. Environment and Development Economics 12 (6), 757–774.

Frederick, S., Loewenstein, G., O'Donoghue, T., 2002. Time discounting and time preference: a critical review. Journal of Economic Literature 40 (2), 351–401.

Gangopadhyay, S., Ramaswami, B., Wadhwa, W., 2003. Access of the Poor to Modern Household Fuels in India. United Nations Development Programme (UNDP) and World Bank Energy Sector Management Assistance Programme (ESMAP).

Gangopadhyay, S., Ramaswami, B., Wadhwa, W., 2005. Reducing subsidies on household fuels in India: how will it affect the poor? Energy Policy 33 2326–2336.

Gundimeda, H., Köhlin, G., 2008. Fuel demand elasticities for energy and environmental policies: Indian sample survey evidence. Energy Economics 30, 517–546.

Howells, M., Alfstad, T., Victor, D., Goldstein, G., Remme, U., 2005. A model of household energy services in a low-income rural African village. Energy Policy 33, 1833–1851.

IMF, 2008. World economic outlook 2008 database. Available at: 〈www.imf.org/external/pubs/ft/weo/2008/01/weodata/index.aspx〉; Referenced 19.5.2009.

Kanagawa, M., Nakata, T., 2007. Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. Ecological Economics 62, 319–329.

Kanagawa, M., Nakata, T., 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36, 2016–2029.

Kaul, M., Dadhwal, V., Mohren, G., 2009. Land use change and net C flux in Indian forests. Forest Ecology and Management 258 (2), 100–108.

Leach, G., 1992. The energy transition. Energy Policy 20 (2), 116–123.

Letschert, V.E., McNeil, M.A., 2007. Coping with residential electricity demand in India's future—how much can efficiency achieve? Technical Report LBNL-63199, Ernest Orlando Lawrence Berkeley National Laboratory.

Mas-Colell, A., Whinston, M.D., Green, J.R., 1995. Microeconomic Theory. Oxford University Press.

Masera, O.R., Saatkamp, B.D., Kammen, D.M., 2000. From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. World Development 28 (12), 2083–2103.

Messner, S., Strubegger, M., 1995. User's guide for message iii. Technical Report WP-95-69, International Institute for Applied Systems Analysis.

NSSO, 2000. Household consumer expenditure survey of India, 55th round URL: 〈http://www.mospi.gov.in/nsso.htm〉.

Pachauri, S., 2004a. An analysis of cross-sectional variations in total household energy requirements in India using micro survey data. Energy Policy 32, 1723–1735.

Pachauri, S., 2004b. On measuring energy poverty in Indian households. World Development 32 (12), 2083–2104.

Pachauri, S., 2007. An Energy Analysis of Household Consumption. In: Changing Patterns of Direct and Indirect Use in India. Springer.

Reddy, A.K., Reddy, B.S., 1994. Substitution of energy carriers for cooking in Bangalore. Energy 19 (5), 561–571.

Reddy, B.S., 1995. A multilogit model for fuel shifts in the domestic sector. Energy 20 (9), 929–936.

Reddy, B.S., 1996. Modelling of competing technologies in the residential sector. Energy Conversion and Management 37 (1), 117–125.

Reddy, B.S., 2003. Overcoming the energy efficiency gap in India's household sector. Energy Policy 31, 1117–1127.

Riahi, K., Grubler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting & Social Change 74, 887–935.

Robinson, M.S., 1996. Addressing some key questions on finance and poverty. Journal of International Development 8 (2), 153–161.

TERI, 2006. National energy map for India: Technology vision 2030. Technical Report PSA/2006/3, The Energy and Resources Institute.

Train, K., 1985. Discount rates in consumers' energy-related decisions: a review of the literature. Energy 10, 1243–1253.

van Ruijven, B.J., 2008. Energy and development—a modelling approach. Ph.D. Thesis, Utrecht University.

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Title	**Risks, costs and equity** **Modelling efficient strategies for climate and energy policy**
Author(s)	Tommi Ekholm
Abstract	The mitigation of climate change can be framed as a problem of risk management on a global scale. Avoiding dangerous interference with ecosystems and human society calls for a global climate policy, which will translate a selected climatic target into economic incentives for reducing greenhouse gas emissions. The necessary emission reductions span many decades and involve actors at different levels of the global economy, from nations to companies and individuals. The reductions entail economic costs which are likely to be unevenly distributed across regions and individuals. Uncertainty in how the climate responds to increased greenhouse gas concentrations creates a risk in that the costs of attaining the selected target may increase. Furthermore, climate policy cannot be isolated from other policy aims; aims that can be contradictory to the aspirations of climate policy. This Dissertation uses numerical scenario modelling to address these issues, and to aid the formulation of efficient climate and energy policies. The perspectives span from the global cost-efficiency analysis of attaining a predetermined temperature target to the consideration of regional equity in mitigation costs, and further to the modelling of capital scarcity and preferences in developing countries. The Articles in this Dissertation share a number of common questions, particularly how costs occurring at different times should be discounted into a single present value, and how the heterogeneity between different actors – regions, countries or households – should be taken into account in policy formulation. On one hand, the results provide guidance on how emissions of different greenhouse gases should be priced and how a global emission market could be used to select the most cost-efficient mitigation measures and to distribute the costs in an equitable manner. On the other hand, the Articles also illustrate potential hindrances for achieving efficient and equitable outcomes. Both types of results share a common aim, which is to explore and quantify the impacts of possible policy options and to facilitate the development of more informed strategies and policies.
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Julkaisun sarja ja numero
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Nimeke	**Riskit, kustannukset ja tasapuolisuus** **Tehokkaiden strategioiden mallinnus ilmasto- ja energiapolitiikkaa varten**
Tekijä(t)	Tommi Ekholm
Tiivistelmä	Ilmastonmuutoksen hillintä voidaan kuvata globaalin mittakaavan riskienhallintakysymyksenä. Ilmastonmuutoksen ekosysteemeille ja yhteiskunnalle aiheuttaman uhan vähentämiseksi tarvitaan maailmanlaajuista ilmastopolitiikkaa, joka luo valittuja ilmastotavoitteita heijastavat taloudelliset kannustimet kasvihuonekaasupäästöjen vähentämiseksi. Tarvittavia päästövähennyksiä tulee toteuttaa useiden vuosikymmenien aikana, ja ne koskevat toimijoita talouden eri tasoilla: valtioita, yrityksiä ja yksittäisiä ihmisiä. Päästövähennyksistä koituvat kustannukset jakautuvat luultavimmin epätasaisesti eri valtioiden ja henkilöiden välille. Epävarmuus ilmaston herkkyydessä kasvaville ilmakehän kasvihuonekaasupitoisuuksille luo riskin, että valittuihin ilmastotavoitteisiin pääseminen aiheuttaa kustannuksia, jotka ovat nykyisiä arvioita suurempia. Lisäksi ilmastopolitiikka ei ole eristyksissä muilta politiikkatavoitteilta, jotka saattavat olla vastakkaisia ilmastopolitiikan tavoitteiden kanssa. Tässä väitöskirjassa esitetään tutkimuksia, joissa numeerisen skenaariomallinnuksen keinoin pyritään avustamaan tehokkaiden ilmasto- ja energiapolitiikkojen muodostamista. Tutkimuksen näkökulma ulottuu globaalin lämpenemistavoitteen kustannustehokkuustarkastelusta alueellisesti tasapuoliseen vähennyskustannusten jakautumiseen ja tästä edelleen tarkasteluihin pääoman riittävyydestä ja kuluttajien energiavalinnoista kehittyvissä maissa. Yhteistä väitöskirjassa esitetyille tutkimusartikkeleille on kaksi erityistä kysymystä: kuinka valittuihin tavoitteisiin päästään kustannustehokkaasti, ja kuinka politiikkoja muodostaessa tulisi huomioida kustannusten kohdentuminen eri ajanhetkillä ja eri toimijoille. Toisaalta tulokset antavat viitteitä sille, kuinka eri kasvihuonekaasuja tulisi hinnoitella ja kuinka kansainvälinen päästökauppa voisi tukea kustannustehokkaiden päästövähennyskeinojen valintaa ja kustannusten tasapuolista jakautumista. Väitöskirjassa havainnollistetaan myös mahdollisia esteitä tehokkaiden ja tasapuolisten lopputulosten saavuttamiselle. Molemmissa tapauksissa taustalla on kuitenkin sama pyrkimys: tarkastella ja kvantifioida eri politiikkavaihtoehtojen vaikutuksia ja parantaa edellytyksiä perusteltujen politiikkojen ja strategioiden muodostamiselle.
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Risks, costs and equity

Modelling efficient strategies for climate and energy policy

Climate change mitigation can be framed as a problem of risk management on a global scale. Avoiding dangerous interference with ecosystems and human society calls for a global climate policy, which will translate a selected climatic target into economic incentives for reducing greenhouse gas emissions. The necessary emission reductions span many decades and involve actors at different levels of the global economy. The reductions entail economic costs, and significant uncertainties are present in the decisions made at different stages of policy and the economy. Furthermore, climate policy cannot be isolated from other policy aims; aims that can be contradictory to the aspirations of climate policy.

This dissertation uses scenario modelling to address these issues. The perspectives span from the global cost-efficiency analysis of attaining a predetermined temperature target to the consideration of regional equity in mitigation costs, and further to the modelling of capital scarcity and energy consumption preferences in developing countries. The results provide guidance on how the emissions of different greenhouse gases should be priced; and how a global emission market could be used to select the most cost-efficient mitigation measures and to distribute the costs in an equitable manner. Through this, the dissertation aims to explore and quantify the impacts of possible policy options, and to facilitate the development of more informed strategies and policies.

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