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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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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

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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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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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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