Doctoral theses at NTNU, 2018:355

Per Ivar Helgesen

Modeling regional effects of energy policy

Combining technical and economic aspects to assess energy policy

NTNU
Norwegian University of
Science and Technology

Per Ivar Helgesen

Doctoral thesis

Doctoral theses at NTNU, 2018:355

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Economics and Management
Department of Industrial Economics and
Technology Management

NTNU

ISBN 978-82-326-3498-9 (printed ver.)
ISBN 978-82-326-3499-6 (electronic ver.)
ISSN 1503-8181

NTNU
Norwegian University of
Science and Technology

Per Ivar Helgesen

Modeling regional effects of energy policy

Combining technical and economic aspects to assess energy policy

Thesis for the Degree of Philosophiae Doctor

Trondheim, November 2018

Norwegian University of Science and Technology
Faculty of Economics and Management
Department of Industrial Economics and Technology Management

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the Degree of Philosophiae Doctor

Faculty of Economics and Management
Department of Industrial Economics and Technology Management

ISBN 978-82-326-3498-9 (printed ver.)
ISBN 978-82-326-3499-6 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:355

Printed by NTNU Grafisk senter

Preface

This thesis is the result of six years' work for the degree of Philosophiae Doctor at the Department of Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). The work started in 2012 as part of the research project Regional Effects of Energy Policy (RegPol), funded by the Research Council of Norway (grant number 216513) and a consortium of industry partners.

My key motivations for starting on this PhD were my ambitions to ensure efficient use of scarce resources and to evaluate policy interventions – an exercise that requires knowledge from many different areas such as economics, mathematics and engineering. I knew that this would require simulation of concurrent behavior from different players in the economy, and quantification of anticipated effects from policy schemes. It was also important for me to work on real-world applications. The practical work in Enova SF has assured my motivation to develop scientific methods for improving impact evaluation. Quantification and attribution of effects are essential for providing decision support on designing policy support schemes. Impact evaluation is structured to answer the question: How would outcomes such as participants' well-being have changed if the intervention had not been undertaken? This involves counterfactual analysis - a comparison between what actually happened, and what would have happened in the absence of the intervention. The project has allowed me to work along all these themes, aligning and reaching both project goals and personal goals during the work. I have especially appreciated the need for hybrid modeling, combining technical fields and economics.

Many people have in different ways made this work possible. First and foremost, I would like to thank my supervisor Asgeir Tomasgard, for your encouragement and advice throughout these years. You have been an excellent guide into the beauty of mathematical programming, and you have provided help and resources when I have needed it. You have also patiently read and commented my work again and again and again. Thank you, Asgeir!

I also want to thank my co-supervisor Olga Ivanova. You have provided deep modeling know-how and enlightening modeling examples, and offered vital contributions for me and the whole project to reach our goals together. Thank you, Olga! Special thanks are due to my co-author Arne Lind from IFE. Thank you for stimulating discussions, constructive viewpoints and fruitful cooperation, which makes problem solving much more fun.

I would like to thank my fellow project participants warmly; the stimulating project manager Arne Stokka and colleagues Gerardo A. Perez-Valdes, Ulf Johansen, Adrian Werner, Lars H Vik, Heidi Bull-Berg and Frode Rømo from SINTEF, as well as IFE participants Kari Espegren, Pernille Seljom and Eva Rosenberg: Thank you for a rewarding collaboration. Working with colleagues like you is a gift, and an important reason why I find my work so exciting. Special thanks to Ruud Egging at NTNU: Your questions and comments have challenged me, and made modeling even more fun. Thanks!

I am grateful for the financial and motivational support from my employer, Enova SF, and I would especially like to thank Geir Nysetvold and Andreas Enge for facilitating this work, making it possible to combine the PhD project with a job in Enova. I want to thank all my colleagues at Enova for supporting me in this work. Special thanks go to Even Bjørnstad and Raquel Santos Jorge, for always being willing to discuss challenges, for providing their excellent advice and for their encouragement. Many thanks also go to Nils Kristian Nakstad, Stein Inge Liasjø and Petter Hersleth in Enova.

During the work I have received inspiration from a lot of people. I will especially mention Paolo Pisciella, Steven Gabriel, Anna Krook-Riekkola, Karl Ludvig Refsnæs, Christoph Böhringer, Thomas Rutherford, Sergey Paltsev, Francesco Piu, Afzal Siddiqui, Ben Hobbs, Stig Ødegaard Ottesen and Stein Erik Fleten.

Many thanks to my parents, Helene and Ivar for all your love and encouragement. Thanks also to my sister Aina, other family and friends for your continuous interest and support. To my children Thor Ivar and Ole Christian: You are more precious than everything else! You make my life rich and worth-while. Finally, I want to thank my wife through more than twenty years, Eva, for standing by my side during this challenging project, despite my frustrations, distant periods and other challenges that we have met together. I love you.

Trondheim, November 2018

Abstract

Environmental and climate issues, increased focus on security of supply as well as the energy system's role in economic growth has led to pressure towards a more sustainable energy system. This requires systematic long term planning on regional, national and international level. Politicians define market conditions, to ensure short and long term optimal resource allocation. Markets also have flaws which justify market interference by introducing policy instruments, trying to improve outcomes from the societal point of view. We develop models that combine technical and economic aspects, seeking to improve the scientific assessment of energy policy options. It is more efficient to have policies simulated in mathematical models, instead of testing them on millions of people.

We combine engineering modeling with economic modeling. The field of energy system modeling belongs largely to an engineering domain. The energy system adheres to physical laws of nature, it includes energy carriers with a variety of physical properties and involves numerous technologies interacting in a supply chain of extraction, conversion, distribution and consumption processes. The energy system is well suited for optimization modeling.

Future societal outcomes result from simultaneous decisions made by multiple actors having their own individual goals. Economic trade and market pricing provide coordination of resources among numerous agents – as if governed by an invisible hand. We apply complementarity modeling, covering concurrent optimization by different agents, reaching equilibrium solutions where no agent has an incentive to change strategy. Furthermore, we apply computable general equilibrium models dealing with firms and households representing the whole economy and cross-sectoral impacts.

We develop a hybrid model framework for Norway, integrating a technology rich bottom-up model with a geographical representation of the energy system and an economic model both at the regional and national level. So far, the majority of hybrid modeling research has

addressed the national or international level. We also focus on distributional impacts across regions, to understand how policy affects local outcomes. The combination of these models makes analysis of policy options viable, also detailed to a sub-national regional level.

The thesis includes four papers.

The first paper, *An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's Laws and Nash-Cournot competition* investigates how different players make investment and production decisions due to the incentives from a tradable green certificate scheme. Network effects from the grid are also demonstrated.

The second paper, *Efficiency and welfare distribution effects from the Norwegian-Swedish tradable green certificates market* builds on the first paper, and quantifies the social welfare cost of incurring a tradable green certificate scheme in a common market shared between Norway and Sweden. Consumers profit from the scheme even though they are paying for it, but deadweight losses turn the isolated social welfare effect from the scheme negative. Location in the network largely determines where new production is being built, and affects the spatial distribution of social welfare outcomes from the scheme.

Paper number three, *Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport* steps from partial equilibrium to general equilibrium modeling. The paper demonstrates hard-linking of large-scale bottom-up and top-down models, and quantifies impacts from reducing CO_2 emissions from transport in 2030 by 50% compared to emissions in 1990.

The last paper, *From linking to integration of energy system models and computational general equilibrium models – effects on equilibria and convergence* compares results from linked and integrated hybrid models. We show that two integrated models find different equilibria, and that the Stackelberg equilibrium from a multi-follower bilevel formulation pareto-dominates the Nash equilibrium. The paper shows that today's commonly utilized linking approach cannot guarantee a pareto-optimal solution, and suggests a general approach towards integrating models.

Abbreviations

BU	Bottom-Up
CGE	Computable General Equilibrium
EEE	Energy-Economy-Environment
GHG	Greenhouse gas
GWP	Global warming potential
IAM	Integrated Assessment Model
LP	Linear Programming
MCP	Mixed Complementarity Problem
NLP	Non Linear Programming
TD	Top-Down

Contents

1 Introduction

This thesis presents techno-economic models for evaluating local regional effects of energy policy. The thesis is divided in two main parts. Part one describes the background, motivation and context for the work. It provides an overview of relevant literature and places the PhD contributions in this scientific landscape. Part two consists of four papers, published in or submitted to peer reviewed journals.

Energy policy is the overarching theme of the thesis, and deals with fundamental needs of the society. Energy is essential for economic development, and the main source of GHG emissions (accounting for 72 percent of all emissions according to C2ES (2017) and 68 percent according to IEA (2017a) page 9). The close relationship between **e**nergy, **e**conomic development and the **e**nvironment is often referred to as the 3Es or trilemma concept (Nakata, Silva, & Rodionov, 2011; WEC & Wyman, 2017). Another example of the importance of energy is found among the 17 sustainable development goals of the United Nations, namely goal 7 which states: "Ensure access to affordable, reliable, sustainable and modern energy for all".

The main global policy objectives include economic growth, security of energy supply and mitigation of the effects of climate change (Santoyo-Castelazo & Azapagic, 2014). Similarly, the three main goals of the energy policy of the European Union are: Security of supply, competitiveness and sustainability (EC, 2010; EU, 2018). 1) Secure energy supplies should ensure the reliable provision of energy whenever and wherever it is needed. 2) Energy providers should operate in a competitive environment that ensures affordable prices for homes, businesses, and industries. 3) Energy consumption should be sustainable, through the lowering of greenhouse gas emissions, pollution, and fossil fuel dependence (EC, 2018). The same three pillars are evident in Norwegian energy policy, which must balance the needs for security of supply, value creation and the environment (NOU, 2012). Energy, Economy and

Environment (EEE) define the three pillars of energy policy, and form the energy policy triangle, depicted in Figure 1.

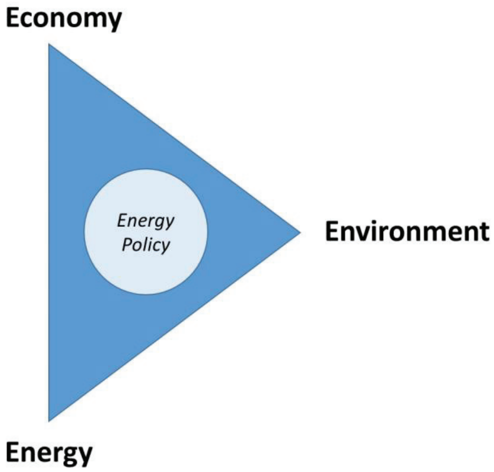

Figure 1 Energy policy triangle (based on NOU (2012))

Motivated by these three pillars of energy policy, we will further discuss energy, sustainability, competitiveness in markets and policy instruments. These broad and complex topics form the information basis of mathematical models, which we use to assess energy policy and analyze effects in spatial geographical regions on subnational level. We provide an overview of such models, describing the broader scientific landscape where the contributions of the thesis belong.

Through the contributions of the papers in Part two, we provide modeling interfaces between the economic system and the energy system. Recognizing the spatial aspects of the energy system motivates better representation of the energy sector and related sectors like transport and industry in regional economic models. We focus on geographical representation of production and demand in energy system models, and the inclusion of trade and transport demands resulting from spatial aspects of such models.

Strengthening the links between policy, energy system models and regional economic models aims to avoid sub-optimization in the energy system, and provide the best basis for energy policy assessment. We develop hybrid model frameworks that integrate technology rich bottom-up models with geographical representation of the energy system and spatial top-down economic models at the regional and national level. We investigate hybrid models analyzing real-world energy policy challenges.

The remaining structure of the thesis is as follows: Part one consists of another four sections numbered from 2 to 5. Section 2 describes the importance of energy, and the challenges we meet from consuming resources at a faster rate than they are renewed. Section 3 describes how consumption is organized in markets where supply matches demand, and resources are employed to the best of society. Nevertheless, markets have flaws and intervention by policy instruments are justified in some settings. Section 4 is about models and describes the modeling landscape in which this thesis delivers its contributions. The section concludes with an overview of taxonomies for classification of energy models. Section 5 explains the research focus, classifies the models we have developed and provides a summary of the papers included in this thesis.

Part two consists of four papers:

1. An Equilibrium Market Power Model for Power Markets and Tradable Green Certificates, including Kirchhoff's Laws and Nash-Cournot Competition
2. Efficiency and welfare distribution effects from the Norwegian-Swedish Tradable Green Certificates Market
3. Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport
4. From linking to integration of energy system models and computational general equilibrium models – effects on equilibria and convergence

2 Energy and sustainability

In this section we provide a broad motivation and basis for the thesis, substantiating the importance of energy and illuminating the associated challenges with sustainability.

2.1 Security of supply

Availability of energy is a fundamental driver for economic prosperity, since energy is an indispensable prerequisite for performing work. We use energy in our everyday life, in order to get work done by using engines or industrial processes, to heat or cool our homes, for lighting, for transportation purposes - in general to live comfortable lives. Our use of energy is vital for our welfare. Lack of energy will produce a crisis. Every nation must ensure security of energy supply.

Since energy is so important, one could believe that there is scarcity of energy. This is generally not true - in principle we have plenty of energy available. The sun provides us with vast amounts of energy every day, by fusing hydrogen into helium. Some of that energy has been converted to chemical energy on Earth through photosynthesis, and stored in the form of energy carriers such as biofuel, coal or oil. These energy carriers can for example be used for heating. The thermal radiation from the sun creates wind and evaporates water on Earth – which respectively represents kinetic and potential energy. This energy can be utilized directly to do mechanical work, or indirectly to generate electric energy which is a very flexible energy carrier that can be transported effectively over long distances. Energy from the sun can also produce electricity directly by using photovoltaics, or it can produce thermal energy by heating water in solar collectors.

Three properties regarding energy are important in assessing security of supply: 1) The *quantity* of available energy, 2) the *quality* of available energy and 3) the *cost* of supplying the necessary amounts of energy with the right quality. We will now discuss these properties.

The quantity matters, because a nation needs sufficient amounts of energy to fuel the economy. As discussed, energy really exists in abundance, and according to the first law of thermodynamics energy is not consumed, it is conserved. However, the amounts of different energy carriers matter, because they represent energy of different quality. We want energy that is able to perform useful work during a process, and we need another concept to convey this property: *Exergy* is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Dincer, 2002). In contrast to energy, which is neither created nor destroyed during a process, some exergy is always destroyed when a process is irreversible, for example when combusting gasoline in an internal combustion engine producing heat that is able to perform work and eventually is lost to the environment. We are not able to reverse the process, and convert the heat back to chemical energy as gasoline. The chemical energy has higher quality - it is able to perform much more work than the energy forms that remains afterwards. The destruction of exergy is proportional to the *entropy* increase of the system together with its surroundings - entropy being a measure of the disorder of a system. The second law of thermodynamics expresses that all activity in the universe derives from matter and energy becoming more disorganized (Hermann, 2006). This means that the entropy of the universe is always increasing. It also means that a perpetual motion machine that converts thermal energy into mechanical work is impossible, since only a reversible process can conserve exergy.

We have established that we need energy of a certain *quality* to perform different types of work. The next property is cost. Humans access and process exergy from many different reservoirs in order to provide energy services. Exergy describes the theoretically extractable work, but it does not describe the ability of humankind to exploit a resource. This ability depends on many factors, for example accessibility and technology. From a technical macro perspective, we have no shortage of energy or even exergy on Earth. Even though each country could have enough exergy from a technical perspective, the *costs* for different technologies vary and many technologies are far from being economically viable. Therefore, the costs necessary to supply and utilize energy and exergy are important, and differ a lot from country to country.

- Countries have access to different *quantities* of energy sources, for example solar radiation or easily exploitable reservoirs of fossil fuels.

- Different energy forms have different energy *quality*, measured as exergy (and hence different economic value).
- Countries have access to different technology and different infrastructure, which is needed to utilize the energy *cost-efficiently* (e.g. electricity grids, oil and gas pipelines, shipping harbours).

2.2 Climate change and sustainability challenges

Humans have become very good at utilizing available resources, creating economic growth and providing increasing welfare. We have learnt how to extract and process fossil fuels in large quantities, giving access to large exergy reservoirs that have improved our quality of life tremendously.

However, sustainable societies and ecosystems must maintain the potential of the sources they use to perform work. The Brundtland Report provides the most popular notion of sustainability (sustainable development): Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The definition provided by the Brundtland Report is a characteristic definition of sustainability (Bithas & Christofakis, 2006). In contrast, most policy decisions are made under an assumption of limitless resources and ecosystem services (Borucke et al., 2013). Nevertheless, if a society consumes exergy[1] resources at a faster rate than they are renewed, it will not be sustainable. The present industrial society is not sustainable (Wall & Gong, 2001). This challenge is expressed in various concepts.

One such concept is the ‘ecological footprint’ (W. Rees & Wackernagel, 1996; W. E. Rees, 1992). Situations in which total demand for ecological goods and services exceed the available supply for a given location are called ‘overshoot’. ‘Global overshoot’ indicates that stocks of ecological capital are depleting and/or that waste is accumulating (Borucke et al., 2013). It is estimated that humanity’s ecological footprint has surpassed the Earth’s biocapacity since at least the mid 1970’s (McBain, Lenzen, Wackernagel, & Albrecht, 2017). The 2017 Edition of the National Footprint Accounts indicates 68% global overconsumption in 2013 (Global Footprint Network, 2017b). A closely related concept is the illustrative calendar date ‘Earth Overshoot Day’, which marks the date when humanity has exhausted

---

[1] In the remaining text we will not distinguish between energy and exergy, and only use the term energy.

nature's budget for the year. In 2017, Earth Overshoot Day fell on August 2 (Global Footprint Network, 2017a).

A similar but perhaps even more pressing perspective is given by the concept of 'planetary boundaries' (Rockstrom et al., 2009b). The planet has boundaries and sustainable development cannot be secured without operating within them (Rockstrom et al., 2009a). The planetary boundaries framework identifies levels of anthropogenic perturbations below which the risk of destabilization of the Earth system is likely to remain low — defining a safe operating space for global societal development. If human activity passes these thresholds (defined as planetary boundaries), there is a risk of irreversible and abrupt environmental change. Anthropogenic perturbation levels of four out of nine planetary system processes exceed the proposed planetary boundaries (Steffen et al., 2015). These four processes are climate change, biosphere integrity, biogeochemical flows and land-system change. Climate change is closely related to energy, as the climate system is a manifestation of the amount, distribution, and net balance of energy at Earth's surface.

The use of energy sources have side effects. Burning fossil fuels like coal, oil and gas emits greenhouse gases such as CO_2. Supplying electricity from nuclear reactors produces radioactive waste, which may escape in nuclear energy accidents. The sustainability of today's use of fossil energy is questioned. Global warming is believed to have impacts such as more frequent extreme weather events, species extinctions, decreasing crop yields and abandonment of populated areas due to rising sea levels. The Intergovernmental Panel on Climate Change (IPCC) has concluded that it is extremely likely (95-100% probability) that human influence was the dominant cause of global warming between 1951-2010 (IPCC, 2014).

The main response to the threat of climate change is the Paris Agreement, adopted 12 December 2015. This agreement aims to keep the increase in the global average temperature well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels (The Paris Agreement, article 2, UNFCCC (2016)). The Paris Agreement requires each country to prepare, communicate and maintain successive nationally determined contributions (NDCs) that it intends to achieve. It is up to the countries to decide their domestic mitigation measures, aiming to achieve their contributions (The Paris Agreement, article 4, paragraph

2, UNFCCC (2016)). Many different policy instruments will be utilized, and they will interfere with the free markets. We discuss this topic in the next section.

3 Markets, competition and policy instruments

> *"Every individual is continually exerting himself to find out the most advantageous employment for whatever capital he can command. It is his own advantage, indeed, and not that of the society, which he has in view. But the study of his own advantage naturally, or rather necessarily, leads him to prefer that employment which is most advantageous to the society."*
> *- Adam Smith (1776), The Wealth of Nations, book IV, chapter ii, 4th paragraph.*

Markets consist of individuals trying to optimize their utility by optimal allocation of their resources enabling consumption of goods, and firms seeking to maximize their profit by acquiring resources and utilizing their technologies in producing goods[2]. In a market characterized by perfect competition, the market prices that ensures equilibrium between supply and demand also provides the necessary guidance for individuals to decide their actions, and reaching an equilibrium that is a Pareto optimum. The "invisible hand" of the free market will transform the individual's pursuit of gain into the general utility of society (Bishop, 1995).

Trade in energy is organized in energy markets. As consumers we are used to the paying the electricity bill or paying for gasoline or diesel at the gas station. Energy actors are developing complex and sophisticated products: hourly pricing, energy trading in future markets, energy performance contracting (EPC) et cetera. Blockchain technology might provide new energy products and create new energy markets.

Nations spend large resources on energy infrastructure and distribution, building power lines for electricity, pipelines for oil and gas and using tankers and trucks for distribution of petroleum products. Energy markets are often strongly regulated. Our observable real-world markets are not perfect markets, they suffer from various types of market failures. Energy

---

[2] By goods we mean both products and services.

policy instruments are implemented to improve market solutions to the benefit of the society. Public market intervention is justified by market failures, such as externalities, public goods, barriers or other market imperfections. Market interventions are not always justified, and the Coase theorem provides us with preconditions making market interventions unnecessary. Coase posited that agents' production and consumption decisions will be economically efficient and remain unaffected from change in a liability rule within the following framework: (a) two agents to each externality (and bargain), (b) perfect knowledge of one another's (convex) production profit or utility functions, (c) competitive markets, (d) zero transactions costs, (e) costless court system, (f) profit-maximizing producers expected utility-maximizing consumers, (g) no wealth effects, (h) agents will strike mutually advantageous bargains in the absence of transactions cost (Hoffman & Spitzer, 1982).

> *"From these considerations it follows that direct governmental regulation will not necessarily give better results than leaving the problem to be solved by the market or the firm. But equally there is no reason why, on occasion, such governmental administrative regulation should not lead to an improvement in economic efficiency. This would seem particularly likely when, as is normally the case with the smoke nuisance, a large number of people are involved and in which therefore the costs of handling the problem through the market or the firm may be high."*
> *- Ronald H. Coase (1960), The Problem of Social Cost, page 18.*

According to Coase, market intervention is not necessary at all, given certain assumptions. Nevertheless, real markets are affected by transaction costs, externalities and public goods. Market regulations are justified when they can alleviate market imperfections, which prevent the market from optimal resource allocation and maximized welfare in the long run.

One example of an externality which called for market intervention is the emissions of chemicals leading to acid rain. Adverse impacts from emissions of sulfur dioxide and nitrogen oxides gained attention during the 1960s. Local effects of SO_2 emissions were initially mitigated by increasing stack heights, and emissions were eventually transported considerable distances via regional atmospheric circulation. The transboundary nature of the acid rain problem complicates the policy making process, because the costs of controlling air pollution are frequently borne in one jurisdiction while the benefits of reducing emissions occur in others (Menz & Seip, 2004). Two major European polluters, United Kingdom and

Germany initially refused to accept that their industrial activities were linked to the acidification damages in neighbor countries (CAFE, 2004). Eventually the insight that acidic depositions cause adverse impacts on water, soils and forests was established. New policies were introduced during the 1980s and 1990s, in the form of regulations, taxes and market-based instruments. A number of international treaties on the long-range transport of atmospheric pollutants have been agreed upon, and emissions have been greatly reduced.

United States has opted to utilize market-based mechanisms to a greater extent than in Europe, where the emphasis has been on "critical loads" and "command and control" regulations (CAFE, 2004). The role of cost-benefit analysis has been limited due to large uncertainties in the relationship between deposition and effects. The concept of critical loads has a weak scientific basis, but has been preferred by decision makers in Europe (Menz & Seip, 2004). Critical loads can be used to map areas sensitive to acidic deposition and illustrate where deposition exceeds acceptable levels, providing an understandable basis to justify market interventions.

Today's challenge of global warming carries many similar properties. The problem has a transboundary nature, and the relationship between emissions and long term effects is uncertain. The challenge seems bigger than acidic depositions, because effects of greenhouse-gas emissions spreads globally instead of regionally, and the global warming depends on the cumulative greenhouse gas emissions (Gillett, Arora, Matthews, & Allen, 2013; Tokarska, Gillett, Weaver, Arora, & Eby, 2016). Cost-benefit calculations involve the utility and welfare of future generations instead of short-term consumption. Possible benefits of emission cuts are uncertain and have large spillover effects, so it is tempting for decision makers to allow local emissions without inflicting taxes and regulations that impose local burdens. Since burning fossil fuels that emit greenhouse gases today may have future societal costs that are not fully reflected in today's prices and not taken into account by market participants, we may conclude that market intervention is justified, and that regional energy policy assessment is a relevant research topic.

3.1 Policy instruments

Market intervention takes many different forms. As mentioned, we may distinguish between "command-and-control" and "market based" approaches. Although economic arguments support market-based approaches, policymakers seem to favor command-and-control approaches such as laws, performance standards or building regulations (Jaffe & Stavins, 1995).

Market-based approaches may be categorized as price-driven or quantity-driven. In the first category, prices are affected by politically decided instruments, such as fixed or ad valorem taxes or subsidies like fixed prices (for example feed-in tariffs), fixed premiums or trade tariffs. Common for these is that the market decides the quantity attained from such policy instruments – for example the amount of renewable electricity produced due to a feed-in tariff, or the amount of emission cuts due to a CO_2-tax.

In contrast, quantity-driven approaches leave price formation to the market forces. Examples of this category are cap-and-trade schemes such as tradable emissions quotas (EU ETS), white certificates for achieving energy savings or green certificates for renewable energy production. A quantity obligation is decided politically, for example defining a quantity of certificates or a limit on emissions. The resulting certificate or quota prices are decided in a financial market.

Let us consider energy policies aiming to decarbonize power - a backbone of the clean energy transformation (IEA 2017). Many public support schemes have supported renewable electricity during the last decade, as a way forward to fight climate change, improve security of energy supply, promoting technological development and innovation, and providing opportunities for employment and regional development (EU 2009, REN21 2015). As of early 2017, 110 jurisdictions had implemented price-driven feed-in policies, whereas 100 jurisdictions had implemented regulatory quantity-driven policies, of which renewable portfolio standards is the most common (REN21 2017). In recent years support instruments are increasingly used in various hybrid policies, especially in combination with competitive bidding (Held et al. 2014, Couture et al. 2015). Support is shifting towards tendering (quantity driven), especially for the support for large-scale projects. In Europe this shift is driven by European Commission State Aid guidelines (REN21 2017).

Energy policy affects energy, economy and the environment, so there will be multiple and potentially conflicting goals. One policy instrument will affect more than one goal, thus multiple policy instruments will interact with each other (Böhringer, Koschel, & Moslener, 2008; Böhringer & Rosendahl, 2010; OECD, 2011). This makes it complicated to assess expected effects of new policy instruments, and to design an optimal policy mix.

3.2 First best versus second best policy interventions

Energy policies aim for many targets. A mix of policy approaches is needed, and different policies interfere with each other. Dealing with market imperfections like externalities, the best solution is to impose a correct price on the externality. For environmental and energy security externalities, a Pigouvian tax (or a permit price) equal to the external cost will internalize the externality, and avoid the market imperfection (Gillingham & Palmer, 2014). This is termed a first-best approach. Such responses are not always feasible, due to for example 1) the costs are uncertain, 2) lack of incentives or 3) weak jurisdiction. Furthermore, actions to correct market failures in another related sector may decrease overall economic efficiency. One has to take into account current distortions in order to find a second-best solution. It may be optimal to intervene in a way that is contrary to usual policy.

The theory of the second best was developed for the Walrasian general equilibrium system.

> *"The general theorem for the second best optimum states that if there is introduced into a general equilibrium system a constraint which prevents the attainment of one of the Paretian conditions, the other Paretian conditions, although still attainable, are, in general, no longer desirable. In other words, given that one of the Paretian optimum conditions cannot be fulfilled, then an optimum situation can be achieved only by departing from all the other Paretian condition."*
>
> *- Lipsey and Lancaster (1956), The General Theory of Second best, page 11.*

One example of the first-best approach is given in Official Norwegian Report (NOU, 2015):

> "*In order to resolve the environmental challenges in an efficient manner, it is necessary for the polluter to take account of the damage inflicted on society. Imposing a Pigou tax is a first-best approach, and governments turn to environmental taxes to internalize the externality.*"
>
> *- Official Norwegian Report (NOU, 2015), English Executive summary, page 1.*

However, in addition to environmental taxes, fiscal taxes are levied on both polluting and clean goods (Bruvoll, 2009). Environmental taxes account for less than 10 % of the national income from taxes and fees in Norway. Taxes create distortions, imposing deadweight losses. Existing tax distortions are one reason that second-best policy approaches must be considered.

Policy instruments are used in a mix. Policy approaches should target certain audiences and efficient design rests on integrated assessments. Grubb, Hourcade and Neuhoff (2015) argue that the development of energy systems rests on a combination of three different domains of socio-economic processes. Each domain implies a need for different policy instruments to transform the energy system towards a sustainable, low-carbon future. The domains operate at different scales of time and decision-making, and explain different characteristics of how energy systems develop. The three domains are termed 'satisficing', 'optimising', and 'transforming' domains. Their characteristics are shown in Table 1.

Table 1 Three domains involved in transformation of global energy systems (based on Grubb, Hourcade, & Neuhoff, 2015)

	Satisficing domain	**Optimizing domain**	**Transforming domain**
Short description	Individuals and firms are apparently not making optimal decisions - the energy efficiency paradox is one example (Jaffe & Stavins, 1994).	Environmental costs are not internalized and priced, cleaner products and technologies are not competitive in the market.	Society is underinvesting in innovation due to knowledge spillover effects, see for example the government's role discussed by Mazzucato (2013).
Economic theory	Behavioral economics	Neoclassical economics	Evolutionary economics
Timescale	Short term	Medium term	Long term
Decision maker	Individuals	Corporations	Public authorities, multinational companies
Policy approach	Regulation and engagement	Taxes, carbon pricing, tradable certificates	Strategic investments, price incentives
Outcome	Smarter choices	Cleaner products and processes	Innovation and infrastructure

We need to understand not only each component, but how the three domains and associated fields of theory relate to each other, and how the corresponding policy approaches can complement and reinforce each other. All three domains need to be addressed to deliver the necessary transformation of the energy system.

In the next section we describe Norwegian climate policy, to exemplify how multiple policy schemes are implemented to reach political goals.

3.3 The Norwegian climate policy landscape

Norway's climate policy is based on agreements reached in the parliament in 2008 and 2012. A law on Norway's climate targets was decided in 2017, stating that climate gas emissions in 2030 should be reduced by 40 % compared to 1990 (KLD, 2017b). Furthermore, Norway shall become a low-carbon society in 2050. Greenhouse gas emissions in 2050 should be reduced by 80-95 % compared to 1990.

The Ministry of Climate and Environment has submitted a climate strategy white paper, describing the policy approaches to reach the climate targets (KLD, 2017a). The main approach is to utilize economic instruments. Statistics Norway lists 48 environmentally related taxes, according to the definition from Eurostat, the OECD and the UN: "A tax whose tax base is a physical unit (or a proxy of it) of something that has a proven, specific negative impact on the environment".

Table 2 Environmentally related taxes (EU/OECD/UN), by type of tax, contents and year (based on Statistics Norway, table 10646)

	2013	**2014**	**2015**	**2016**
Energy taxes (14 types) – CO_2, electricity, diesel, petrol , …	38 437	39 923	40 946	41 755
Pollution taxes (14 types) – plastic packaging, lubricating oil, glass packaging, …	1 905	1 979	2 069	2 176
Resource taxes (9 types) – hydroelectric license fees, research tax fisheries, hunting, …	872	960	890	1 217
Transport taxes (11 types) – motor vehicle registration tax, annual tax on motor vehicles, …	32 320	30 962	29 946	30 441
Environmentally related taxes, total (48 types)	**73 534**	**73 824**	**73 851**	**75 589**

When taxes are introduced, tax *exempts* may also provide financial incentives for sustainable choices. The Norwegian parliament has provided powerful financial consumer incentives to buy zero emission cars. Battery electric vehicles and fuel cell electric vehicles (using hydrogen) are exempt from registration tax, value added tax and road tolls, they pay a lower annual fee, they are allowed to drive in the bus lane, they enjoy free parking in municipal car parks and run free on ferries (Bjerkan, Nørbech, & Nordtømme, 2016; Figenbaum, Assum, & Kolbenstvedt, 2015). Zero emission battery electric vehicles reached a market share of more than 20 % of new registered passenger cars in 2017. More than 50 % of all new passenger cars in Norway had an electric engine in 2017 (in either a battery electric or a hybrid passenger car) (OFV, 2018).

In addition to national taxes, Norway cooperates with the European Union (EU) on reaching climate targets and joined the EU emissions trading system (EU ETS) on 01.01.2008. This cap and trade system for greenhouse gas emissions is considered as one of the main climate policy instruments in Norway. The larger greenhouse gas emitters must buy one EU allowance unit (EUA) for each tonne of CO_2 emissions (as well as certain N_2O or PFC emissions converted to CO_2 equivalents according to their GWP values). Around 150 Norwegian installations are obligated to buy allowances for their emissions, accounting for approximately half of total national emissions.

Furthermore, a number of public authorities run programs for financial support to climate related projects (beyond research projects supported by the Research Council of Norway). Around 40 climate related support schemes exist, and they are run by Enova, Gassnova, Innovation Norway, Norwegian Environment Agency, Norwegian Agriculture Agency and the Norwegian Coastal Administration.

Other policy instruments are relevant as well, such as the common green certificate scheme with Sweden which rewards renewable electricity production. The goal is to increase the renewable share of total energy consumption, thus contributing to comply with the EU Renewable Energy Directive that defines legally binding targets for the national renewable energy share (EU, 2009).

Finally, there is consensus on a series of other measures that will be implemented in Norway as well. These include regulatory measures like phasing out fossil heating oil and introducing stricter energy requirements for the building sector as well as measures like increasing climate research, maintaining or increasing the carbon stores in forests, developing biogas and strengthening the role of the railway in the transport system (KLD, 2014).

Thus, a large share of activities leading to greenhouse gas emissions in Norway are covered by multiple policy instruments (for example taxes, quotas and support schemes). This emphasizes the need for analysis tools being able to assess second best policy interventions.

4 Models

"All models are wrong, but some models are useful!"
- George Box

Policy-makers need to understand the effectiveness and cost of policies whose purpose is to shift energy systems toward more environmentally desirable technology paths (J. C. Hourcade, Jaccard, Bataille, & Ghersi, 2006). Scientifically, we would like to assess energy policies by comparing a market adaption including the policy instrument with a counterfactual business-as-usual market adaption. We should compare whether political goals are achieved, the benefits and the cost of the policy approach. Unfortunately, it is difficult to conduct large-scale experiments and measure the effects of different policy approaches. It would be expensive, it would take long time and the effects would be highly uncertain due to other simultaneous changes in relevant factors, differences in populations and numerous other factors. Instead we employ mathematical models to study the effects of policies, allowing us to define scenarios representing different futures or alternative assumptions.

We do utilize computational models which allow much more detail and complexity than simple analytic models. Numerical simulation removes the need to work in small dimensions, and accommodate systematic analysis of economic problems where analytical solutions are either not available or do not provide adequate information (Shoven & Whalley, 1992). For instance, tax-policy models can simultaneously accommodate several taxes. This is relevant, since Norway has 48 different types of environmentally related taxes (as shown in Table 2). Taxes compound in effect with other taxes, so it is important when evaluating changes in only one tax to take other taxes into consideration. Quantitative simulations to evaluate alternative policy measures play a key role in applied economic research (C. Böhringer, T. Rutherford, & W. Wiegard, 2003).

The use of scenarios allows us to undertake 'what if, then' experiments (Nakicenovic et al., 2003) which paint a picture of a future, not the future. Modelled scenario analysis does not constitute predictions of the future (Alcamo et al., 2005). Rather than predicting the future, modelled scenario analysis can be used to enhance understanding (Clarke, Weyant, & Edmonds, 2008).

Understanding energy-economy coupling is crucial when we want to analyse effects of energy policy. Modelled scenario analysis may be processed under different assumptions, and thus indicate important areas of incomplete knowledge. One example: Pérez de Arce and Sauma (2016) compare four different incentive policies for renewable energy in an oligopolistic market with price-responsive demand: carbon tax, feed-in tariff, premium payment and quota system. They find that the effectiveness of the different incentive schemes varies significantly depending on the market structure assumed.

There is a wide range of quantitative models for assessing the causal chains between a proposed policy change and its potential economic, environmental, and social impacts (Böhringer & Löschel, 2006). The models in this thesis represent markets where supply and demand of goods balance, at a price consistent with this supply and demand. This combination of price, supply and demand constitutes an equilibrium. A *partial* equilibrium model focuses on a particular commodity or sector, and may include detailed information specific to the market being analyzed. In this thesis we focus on energy, and the most versatile and important energy carrier is electricity. Decarbonized power is a backbone of the clean energy transformation (IEA, 2017b). The trade of electricity in power markets is characterized by the transmission grid, and the physical laws that govern power transportation in the grid. These laws complicate the modeling. We have included AC characteristics (through a DC approximation) in the analysis, and we see how this affects the location of new generation projects and consequential welfare distribution effects.

The transmission grid characteristics are governed by physical laws. We must also take into account legal and social laws – for example assumptions regarding market competition. International electricity markets have been liberalized and redesigned during the last three decades. Norway was one of the earliest countries, deregulating the electricity market in 1991 (Bye & Hope, 2007). Many studies since then have focused on market competition and possible misuse of market power (S. Borenstein & Bushnell, 1999; Borenstein, Bushnell, Kahn, & Stoft, 1995; J. Bushnell, 2003). Although many policies have been implemented to promote competition, there is still evidence of market power in electricity markets (J. B. Bushnell, Mansur, & Saravia, 2008; Dahlan & Kirschen, 2012; Mirza & Bergland, 2015; Pérez de Arce & Sauma, 2016). On the other hand Neuhoff (2003) argues that a system where the system operators integrate national energy spot markets and transmission planning is helpful in mitigating the extent of market power being exercised. Amundsen and Bergman (2007) conclude that the Nordic countries have created an integrated wholesale market that dilutes market power that otherwise would have been a feature of each of the national markets. Amundsen and Bergman (2012) also study to what extent market power on a tradable green certificate market can be used to affect an entire electricity market, and conclude that Swedish producers could exercise market power using the national tradable green certificates (TGC) market, but that this problem is eliminated by opening the TGC-market for other Nordic countries (which is the current situation).

A partial equilibrium model may focus on complex technical aspects within a defined area. From a market viewpoint, such models detail relationships mainly on the supply side. A natural extension would be to cover demand from the whole economy across different sectors. Also, the supply side needs to cover multiple commodities and sectors, since demand for commodities depend on each other - being substitutes or complements. The need to extend both the demand side and supply side brings us to two competing modeling philosophies, which may be labeled “top-down” and “bottom-up” perspectives.

4.1 Bottom-up and top-down models

To extend the modeling scope of both supply and demand, what typically emerge are large-scale bottom-up models describing supply in detail, and large-scale top-down models describing the demand side from the national economy (with data from national accounts). These two perspectives have complementary strengths and are useful to link, offering a hybrid of the two perspectives (J. C. Hourcade et al., 2006). The two perspectives are pictured in Figure 2.

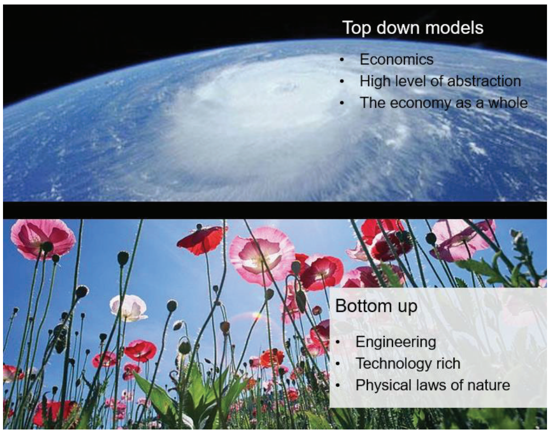

Figure 2 Bottom-up and top-down models

4.1.1 Bottom-up models

Bottom-up models characterize the energy system with great technological detail, and focus on the integration of technology cost and performance data (Fortes, Pereira, Pereira, & Seixas, 2014; M Grubb, Edmonds, ten Brink, & Morrison, 1993). Bottom-up models may be divided into four types (Fleiter, Worrell, & Eichhammer, 2011; Herbst, Reitze, Toro, & Jochem, 2012):

- Optimisation models
- Simulation models
- Accounting models
- Other, for example multi-agent models

Optimisation models optimise the choice of technology alternatives with regard to total system costs to find the least-cost path. Such models are also categorised as partial equilibrium models, since they balance demand and supply in the covered sectors. *Simulation models* constitute a very broad and heterogeneous group. Their modelling aspects depart from the pure optimisation framework. They can include econometrically estimated relations. Large simulation models can include partial optimization (e.g. from a company perspective), and can consist of different modules covering more aspects. *Accounting models* are less dynamic, and do not consider energy prices. These models mainly apply exogenous assumptions on the technical development.

Multi-agent models are a broader modelling class than the optimisation models, since they include the simultaneous optimisation by more agents.

The borders are not sharp and well defined, and some models may show characteristics of more than one group. Models are often developed over time and may change type. Table 3 below gives examples of engineering bottom-up models of the different types, covering most of the energy demand (different sectors and energy carriers). Further descriptions and numerous references can be found in Connolly, Lund, Mathiesen, and Leahy (2010), Fleiter et al. (2011), Huppmann and Egging (2014), Balabanov (2011) and Wolfgang (2006).

Table 3 Examples of engineering bottom-up models

Model type	Model
Optimisation models	ENERGYPLAN IKARUS MESSAGE PRIMES TIMES/MARKAL
Simulation models	ENPEP INFORSE LEAP MESAP PLANET POLES
Accounting models	MAED MED-PRO MURE
Multi-agent models	LIBEMOD MULTIMOD

In the thesis work we want to link the bottom-up model to a top-down economic model, and cover the full energy system with all energy carriers. This requirement rules out the multi-agent models, which cover detailed agent behaviour but only parts of the energy system. In this thesis we focus on normative optimization models, as opposed to descriptive simulation and accounting model. The optimization models constitute the most homogenous group with certain characteristics that can be exploited to form a sound hybrid model.

Giannakidis, Labriet, ÓGallachóir, and Tosato (2015) provide a comprehensive range of methodological approaches and case studies of good modelling practice at national and international scale from the IEA ETSAP[3] energy technology initiative. They demonstrate how energy system models are used to answer complex policy questions relating, amongst others, to optimal allocation of energy resources, energy security and climate change mitigation. The optimization models combine a detailed technology rich database with consequential economic costs, providing useful guidance into how to achieve policy goals (e.g. emissions targets) using a least-cost approach. Various examples of model coupling providing additional insight into macroeconomic consequences are provided, focusing on global perspectives (Glynn et al., 2015a) and national perspectives (Glynn et al., 2015b).

DeCarolis et al. (2017) describe steps associated with analysis using energy system optimization models, provide guidance and formalize best practice for such work. They are aware of the need to capture economic effects of a perturbation beyond the boundaries of the energy system. They state that capturing both the bottom-up technical detail in an energy system optimization model and the top-down consistency in a CGE is an active area of ongoing research (page 191) – resonating well with the work of this thesis.

4.1.2 Top-down models

Top-down models are usually economic models which analyze aggregated behavior based on economic indices of prices and elasticities (M Grubb et al., 1993). They typically cover the economy as a whole, and divides it in production sectors and consumption categories (Fortes et al., 2014). Top-down models can be divided in four types (Herbst et al., 2012):

- Input-output models
- Econometric models
- Computable General Equilibrium models
- Other, for example system dynamic models

---

[3] Energy Technology Systems Analysis Program

Input-output models follow the monetary flows between different sectors of the economy, and include both intermediate and end-use deliveries from each sector. From these interrelations one can estimate monetary effects of economic shocks or structural changes in the economy. These models are not dynamic in prices, and assume that prices are given exogenously. *Econometric models* deal with time series analysis and estimate statistical relations between economic variables over time in order to calculate projections from the resulting model. *Computable general equilibrium models* (CGE) are based on microeconomic theory and calculate how both prices and activities in all sectors change, in order to reach a general equilibrium in the economy. Like the first group, these models also build on the input-output data from national accounts. *System dynamic models* have pre-defined rules for the behaviour of different actors in the model, and are able to make complex non-linear simulations on this basis.

In this thesis we focus on computable general equlibrium models for top-down modelling. Input-output models do not take price effects into account, which makes them less useful for long-term simulations. We want to analyse long term effects of energy policy, and the statistical relations based on historical data will not necessarily remain for 30 years in the future. The Lucas critique argues that econometric models cannot predict effects of a change in economic policy on the basis of relationships observed in historical data (Lucas, 1976). The system dynamic models usually have a narrower focus, and are less general than the CGE models. Top-down CGE models describe the whole economy, and emphasize the possibilities to substitute different production factors in order to maximize the profits of firms and satisfy market clearance conditions (Helgesen, Lind, Ivanova, & Tomasgard, 2018).

A CGE model is formulated as a system of simultaneous equations representing the demand for goods by consumers, the supply of goods by producers and the equilibrium condition that supply equal demand on every market. We assume that each consumer acts to maximize his utility, and each producer acts to maximize his profit. If we assume perfect competition, then each producer and consumers regards the prices paid and received as independent of his own choices. Arrow and Debreu (1954) prove the existence of a general equilibrium for such a competitive Walrasian economy. The first successful implementation of an applied general equilibrium model without the assumption of fixed input-output coefficients was made in 1960 by Leif Johansen (Johansen, 1960), as noted by Dixon and Jorgenson (2013). CGE models are consistent with micro-foundations, i.e. demand and supply functions contained in the models are consistent with utility and profit maximization calculus which is the core of the neoclassical economic theory of consumer and producer behaviour (Bernow, Rudkevich, Ruth, & Peters, 1998). Thus, CGE models are not subject to the Lucas critique.

CGE models are widely employed by national and international organizations (EU Commission, IMF, World Bank, OECD, etc.) for economic policy analysis at the sector-level as well as the economy-wide level. CGE analysis constitutes a powerful scientific method for the comprehensive ex-ante simulation of adjustment effects induced by exogenous policy interference (C. Böhringer, T. F. Rutherford, & W. Wiegard, 2003). A survey of well-known CGE models for sustainability impact assessments is presented in Böhringer and Löschel (2006). The substitution possibilities between energy and other production factors are captured in production functions, which describe the changes in fuel mixes as the result of price changes under certain substitution elasticities.

One weakness with the smooth CGE production functions is that they can result in violation of basic energy conservation principles. The widely used constant elasticity of substitution (CES) production function aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy flows (Sue Wing, 2006). Top-down representations of technologies can also produce fuel substitution patterns that are inconsistent with bottom-up cost data (Lanz & Rausch, 2011). Thus, linking with bottom-up models may improve upon some significant weaknesses.

4.2 Assessing energy policy by the comparative statics method – uniqueness of equilibria

Both a top-down CGE model and a bottom-up optimization model search for competitive economic equilibria, where supply equal demand. Prices are assumed to be flexible, and resulting from market dynamics. The agents represented in the models behave consistently, and no agent has an incentive to change its behavior in the equilibrium solution. These models ensure efficient use of resources. If perfect competition is assumed, then the top-down complementarity and bottom-up optimization models ensure that resources are used optimally to ensure maximum welfare for society. They are normative models, as opposed to descriptive models such as simulation, accounting or econometric models.

Policy assessment is made by comparing the market equilibrium including the policy instrument with a counterfactual unperturbed business-as-usual solution. This method of comparing equilibria before and after adjustment due to the policy instrument is the comparative statics method. The changes in variable values from the initial equilibrium to the new one is used as an indication of the changes that would be expected in the corresponding variables in the economy, if the simulated policy change were to occur. If there is more than one possible equilibrium after the parameter change, the method becomes problematic (Kehoe, 1991). The comparative statics method assumes stable and unique equilibrium solutions.

Multiple equilibria could also create convergence problems. A natural way to link models is to exchange solutions between models and run iterations in order to converge numerically to an equilibrium where no agent has any incentive to change behavior. If the CGE-model may alternate between different solutions, such an iteration procedure would be unstable, and may never converge.

Bottom-up optimization models are usually formulated as linear programs (LP), while top-down CGE models are highly nonlinear. They may be solved as nonlinear programs (NLP), but are typically formulated and solved more efficiently as mixed complementarity problems (MCP), based on the framework of Mathiesen (1985). This modeling exploits the complementarity features of economic equilibrium: 1) Each activity that runs must reach zero profit. If the profit is negative, it will not run. 2) Each good must have a price that clears the market (demand equals supply). The good can be oversupplied only if the price is zero. 3) Consumer utility is assumed to be insatiable, thus every household will spend all its income (the model may include opportunities to save income for future consumption).

An LP problem may have zero, one or indefinitely many solutions. An NLP may have zero, one or indefinitely many solutions, but unlike an LP it may have an integer number of solutions (two or more). Since CGE models are nonlinear, they may have an integer number of solutions. Dierker (1972) shows that if there are more than one solution, the number of solutions has to be an odd number.

Known conditions that are sufficient for uniqueness are highly restrictive. If either the weak axiom of revealed preference (WARP) or gross substitutability (GS) is satisfied by the consumer excess demand function, then a pure exchange economy has a unique equilibrium (Kehoe, 1985). For CGE models involving production, Mas-Colell (1991) provides sufficient conditions for uniqueness by proving that economies with CES utility and production functions whose elasticities of substitution are greater than or equal to one are guaranteed to have a unique equilibrium in the absence of taxes and other distortions. These conditions are restrictive, and introduction of taxes further complicates formulation of sufficient conditions for uniqueness (Kehoe, 1998).

There are few examples of models with multiple equilibria. Kehoe provides an overview with numerical examples (Kehoe, 1998). Whalley and Zhang (2011) show tax-induced examples with 3 equilibria in a 2-individual 2-good pure exchange economy, and they are able to find 5 equilibria in a 3-individual 2-good pure exchange economy (Whalley & Zhang, 2014). There are also a few examples of multiple equilibria in CGE models with production and increasing returns. Mercenier (1995) reports two equilibria in a large-scale applied world economy CGE model. Denny, Hannan, and O'Rourke (1997) find two equilibria while studying tax reforms using a CGE covering the Irish economy. The possibility of multiple equilibria means that convergence of solution algorithms cannot be guaranteed (Böhringer & Rutherford, 2009). Mathiesen (1987) discusses why theoretical results concerning convergence are few, but for a specific example with linear complementarity problems he is able to proof convergence if one solution exists. The possibility of multiple equilibria prohibits us from studying alternative decomposition methods for the integrated models that relies on convexity, for example Benders decomposition.

We assume solutions to our hybrid models to be unique, although we are not able to prove this. Our numerical methods have enabled us to detect possible alternative equilibria. On the occasions that this has occurred, alternative equilibria have been due to modeling weaknesses, which we have eliminated. We have demonstrated stable convergence from realistic large-scale hard-linked bottom-up and top-down models.

The next two sections expand the modeling landscape, by covering environmental and behavioral aspects in more detail. Then in section 4.5 we present different taxonomies suitable for characterizing EEE models.

4.3 Integrated Assessment models

A broad definition is that integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework (Weyant et al. 1996). The typical aim is to combine scientific and economic aspects of climate change, in order to assess policy options for climate change (Kelly & Kolstad, 1999). The activity aims to generate useful information for policy making rather than to advance knowledge for knowledge's sake, hence the term "assessment".

Environmental problems cross different academic disciplines, and IAMs usually consists of many hard-linked modules (Parson, FisherVanden, 1997), not only bottom-up and top-down which is the prominent hybrid model approach of energy-economy models.

IAMs represent the global socio-ecological system, which extends into the cultural-economic sphere of causation and the biophysical sphere of causation (Pauliuk, Arvesen, Stadler, & Hertwich, 2017). Because the relationships within and between the various biogeochemical and socioeconomic components of the earth system can be quite complex, a number of quantitative models have been developed to study earth systemwide climate changes and the effect of various types of public policies on projections of future climate change (Weyant, 2017). Key components of an IAM include climate and sea level modules, human activities (for example the energy system and agriculture, livestock & forestry), atmospheric composition (for example the ocean carbon cycle and atmospheric chemistry) and ecosystems (for example the terrestrial carbon cycle, hydrology and crops & forestry) (Weyant et al., 1996). One IAM may include a complete energy system model or a computable general equilibrium model as a separate module of the integrated assessment model. Since IAMs aim to model the biophysical world, they often have a global coverage with highly aggregated regional representation.

Integrated assessment models have been used extensively in assessment reports from the Intergovernmental Panel on Climate Change (IPCC). The Fifth Assessment Report (AR5) Scenario Database comprises 31 models and 1 184 scenarios (Krey et al., 2014).

Reviewing the structure of IAMs poses some difficulties: First, IAMs draw upon the specific knowledge of many scientific disciplines ranging from ecosystem science to macroeconomics and integrate it into a unique modelling structure. Second, IAMs with global scope are a very diverse group of models with more than 30 members. Third, since many IAMs have been developed over several decades, their documentation is often scattered across many different journal articles, reports, and other documents, and for several central aspects of some models, no publicly available documentation exists (Pauliuk et al., 2017).

Since IAMs are a diverse group of models covering many scientific disciplines, they are hard to classify. Weyant (2017) divides IAMs in two basic types: 1) detailed process IAMs and 2) benefit–cost. These types handle climate change impacts differently. The first type is more disaggregated and seek to provide projections of climate change impacts at detailed regional and sectoral levels. Impacts may be measured using economic valuation, but some models also use projections of physical impacts such as reductions in crop growth, land inundated by sea level rise, and additional deaths from heat stress. In contrast, benefit-cost IAMs provide a more aggregated representation of climate change mitigation costs, and aggregate impacts by sector and region into a single economic metric.
One systematic comparative documentation with descriptions of ten widely applied IAMs are provided from the EU-ADVANCE project (Winning, 2013).

In the next section we discuss how the scope for IAMs could be widened further.

4.3.1 Extending integrated assessment models with insights from industrial ecology

One possible extension of integrated assessment models is adding new system linkages from industrial ecology (based on Pauliuk et al. (2017)). The scientific field of industrial ecology focuses on the empirical analysis of the future industrial system. Industrial ecology quantitatively analyses specific linkages in the biophysical basis of society. The central methods are 1) life cycle assessment, 2) environmental input-output analysis, 3) material flow analysis, 4) analysis of industrial symbiosis and 5) urban metabolism studies.

Researchers in industrial ecology have identified the following linkages in society's biophysical basis as important determinants of sustainable development: 1) global supply chains and their environmental, economic, and social impacts, 2) the linkage between capital services, capital stocks, and capital formation, 3) material cycles and their development over time, 4) co-production and by-production, waste generation and use, and 5) the link between the urban fabric and consumption patterns.

The scope between IAMs and industrial ecology is overlapping, but the two fields have remained largely disconnected. IAMs ignore material cycles and recycling, incoherently describe the life-cycle impacts of technology, and miss linkages regarding buildings and infrastructure. Adding IE system linkages to IAMs adds new constraints and allows for studying new mitigation options, both of which may lead to more robust and policy-relevant mitigation scenarios.

One example is the steel material cycle. Milford, Pauliuk, Allwood, and Müller (2013) show that the global emissions mitigation potential of material efficiency in the steel cycle is up to 1.5 Gt CO_2e/year in 2050, which is about half of the sector's total emissions. Consequently, recycling, lightweighting, and other material efficiency strategies should be part of technology-rich IAMs, which would allow them to assess a wider spectrum of emissions mitigation strategies than is currently the case.

4.4 Socio-technical energy transition (STET) models

We now return from integrated assessment models, and look at another extension of energy modelling. Several authors argue that energy modelling should go beyond a technology and economics focus, and incorporate broader behavioral and social insights (Foxon, 2013; Hughes & Strachan, 2010; Trutnevyte, Stauffacher, Schlegel, & Scholz, 2012).

Pfenninger, Hawkes, and Keirstead (2014) examine the challenge of integrating human behavior and social risks and opportunities. This challenge is treated further by Li, Trutnevyte, and Strachan (2015), who provide a taxonomy for so-called socio-technical energy transition (STET) models - integrating both quantitative modelling and conceptual socio-technical transitions addressing societal actors, socio-political dynamics and the co-evolving nature of society and technology. Thus, an energy modelling paradigm for integrating both quantitative modelling and conceptual socio-technical transitions may emerge.

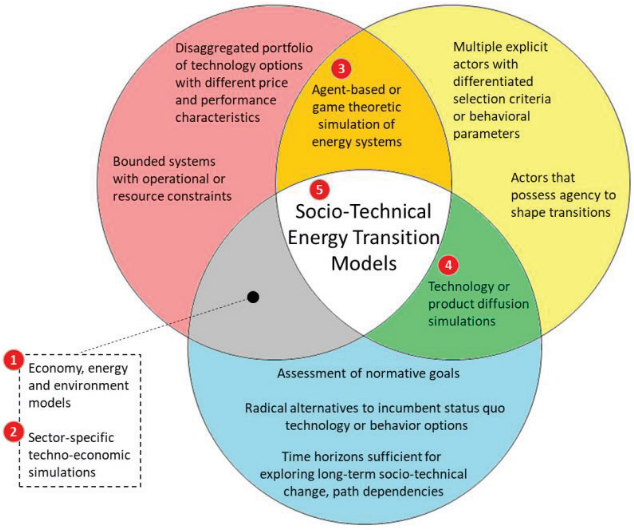

Figure 3 Taxonomy of social-technical energy transition (STET) models (based on Li et al. (2015) and Li and Strachan (2017))

Socio-technical energy transition models combine techno-economic detail, behavioral heterogeneity and transition pathway dynamics to capture elements of socio-technical change in a formal analytical framework.

Quantitative models typically make optimistic assumptions regarding human behavior and decision making, overestimating the speed at which socio-economic and technological systems can adapt. Approximating such a first-best policy landscape often restricts the insights. Empirical studies of socio-technical change have shown that technological diffusion is often influenced by actors and institutions interacting under less ideal, second-best conditions.

Li and Strachan (2017) quantify these factors in a formal energy model as landscape and actor inertia, and employ them in a dynamic stochastic socio-technical simulation of technology diffusion, energy and emissions. Their results illustrate how socio-technical inertia may significantly blunt future efforts to achieve climate targets

There are parallels from the taxonomy of socio-technical energy transition models to the three domains (Grubb et al., 2015) described in Table 1, see Table 4 below.

Table 4 Correspondence between socio-technical energy transition model taxonomy and the three domains involved in transformation of global energy systemes

Socio-technical energy transition models (Li et al., 2015)	Domains involved in transformation of global energy systems (Grubb et al., 2015)
Techno-Economic Detail	Optimizing domain
Explicit Actor Heterogeneity	Satisficing domain
Transition Pathway Dynamics	Transforming domain

4.5 Classification of energy models

Since EEE modeling is widespread and diverse, several taxonomies have been developed to classify such models. The rationale is to simplify comparison of models, and enabling decision makers to choose a suitable model for decision support. Unfortunately, the spectrum of models is large, and a taxonomy needs to use many attributes to characterize the models. In this section we review energy system model taxonomies. A tabular comparison is provided in Table 5.

M Grubb et al. (1993) draw distinctions along six dimensions of classification: 1) Top-down and bottom-up 2) Time horizon 3) Sectoral coverage, 4) Optimization versus simulation techniques, 5) Level of aggregation and 6) Geographic coverage. J.-C. Hourcade et al. (1996) on the other hand, focus on three other dimensions: 1) Purpose, 2) Embedded structure and 3) External assumptions. These classifications are combined in van Beeck (1999), where nine characteristics are defined. This taxonomy is further detailed in van Beeck (2003), where ten characteristics are used to characterize energy models.

Nakata (2004) focuses on two characteristics, namely 1) top-down versus bottom-up, and 2) equilibrium, optimization and simulation models, while Nakata et al. (2011) list seven characteristics as a summary of the model's design approaches (referring to van Beeck (1999), who listed nine characteristics).

Jebaraj and Iniyan (2006) review six different classes of energy models without a clearly defined classification structure. They do separate models based on the underlying methodology, and inclusion of specific renewable technologies, namely solar, wind and bioenergy.

Connolly et al. (2010) review computer tools for analyzing the integration of renewable energy, based on a survey distributed to tools developers. The survey had five sections. 1) Availability (number of users, type of tool listing 7 alternatives), 2) Geographical, 3) timeframe, time-step, 4) sector coverage 5) renewable energy penetration. 68 tools were considered, 37 tools were included in the final analysis.

Herbst et al. (2012) are mainly focusing on top-down versus bottom-up, with further sub-classifications, thus using a two-level hierarchy.

Pfenninger et al. (2014) group energy system models into four categories: 1) energy systems optimization models, 2) energy systems simulation models, 3) power systems and electricity market models, and 4) qualitative and mixed-methods scenarios, thus defining their classification according to the underlying methodology.

Timmerman, Vandevelde, and Van Eetvelde (2014) presents a classification of techno-economic energy models, focusing on low carbon business park energy systems. In such applications, the analytical approach is bottom-up. Their classification is primarily based on the underlying methodology, but includes also purpose, geographical coverage, time horizon, temporal detail and demand characteristic (see Timmerman et al. (2014), table 1 on page 76).

Hall and Buckley (2016) define a classification schema with 14 characteristics, extending the 10 characteristics in van Beeck (2003). They merge classifications from various sources to find a broad set of categories that differentiate between models. The authors demonstrates classification of a random set of 22 (out of nearly 100) energy systems models, using their classification schema.

Schinko, Bachner, Schleicher, and Steininger (2017) define nine characteristics, mainly based on van Beeck (1999).

Table 5 Taxonomies for model classification

Grubb, Edmonds, ten Brink, Morrison (1993)	Hourcade et al. (IPCC AR2) (1996)	Van Beeck (1999)	Van Beeck (2003)	Nakata (2004)	Jebaraj and Iniyan (2006)	Connolly, Lund and Mathiesen (2010)	Nakata, Silva and Rodionov (2011)	Herbst, Toro, Reitze and Jochem (2012)	Timmerman, Vandevelde and Van Eetvelde (2014)	Hall and Buckley (2016)	Schinko, Bachner, Schleicher and Steininger (2017)	
	Purpose	General and specific purpose	The perspective on the future				Purpose		Purpose	Purpose - general and specific	General purpose and intended use	*forecasting, exploring, backcasting*
			Specific purpose									*energy demand, energy supply, impact assessment, appraisal, environmental, integrated, modular*
Level of aggregation	Internal structure	Model structure: internal & external assumptions	Model structure: internal & external assumptions							Model structure: internal & external assumptions	Model structure and exogenous assumptions	*endogenization, non-energy sectors, end-uses, supply technologies, supply or demand analysis tool*
	External assumptions											
Top-down, bottom-up		Analytical approach: Top-down versus bottom-up	Analytical approach: Top-down versus bottom-up	Top-down, bottom-up		Top-down, bottom-up	Analytical approach	Top-down, bottom-up	(Bottom-up only)	Analytical approach	Analytical approach and conceptual framework	*top-down, bottom-up, hybrid, other*
Optimization versus simulation techniques		Underlying methodology	Underlying methodology	Underlying methodology	Underlying methodology	Underlying methodology	Methodology	Underlying methodology	Underlying methodology	Underlying methodology	Underlying methodology	*econometric, macroeconomic, microeconomic, economic equilibrium, optimization, simulation, stochastic/Monte-Carlo, spatial, multi-criteria, accounting*
		Mathematical approach	Mathematical approach			Mathematical approach	Mathematical approach	Mathematical approach		Mathematical approach		*linear programming, mixed-integer programming, dynamic programming, fuzzy logic, agent-based programming*
Geographic coverage		Geographical coverage	Geographical coverage	Geographical coverage		Geographical coverage	Geographical coverage		Geographical coverage	Geographical coverage	Geographical coverage	*global, regional, national, local, single-project*
Sectoral coverage		Sectoral coverage	Sectoral coverage			Sectoral coverage				Sectoral coverage	Sectoral coverage	*energy sectors, other specific sectors, overall economy*
Time horizon		Time horizon	Time horizon			Time horizon	Time horizon		Time horizon	Time horizon	Time horizon	*short, medium, long-term*
		Data requirements	Data requirements				Data requirements			Data requirements	Data requirements	*qualitative, quantitative, monetary, aggregated, disaggregated*
						Time step			Temporal detail	Time step	Path dynamics (comparative static vs. dynamic)	*minutely, hourly, monthly, yearly, five-yearly, user-defined*
					Renewable technology inclusion	Renewable technology inclusion				Renewable technology inclusion		*hydro, solar pv, solar thermal, geothermal, wind, wave, biomass, tidal*
										Storage technology		*pumped hydro, battery, compressed-air, hydrogen*
									Demand characteristic	Demand characteristic - end user sector inclusion		*transport, residential, commercial, agricultural*
										Cost inclusion		*fuel prices, fuel handling, investment, fixed operation & maintenance, variable operation & maintenance, co2*

These taxonomies can be used to classify energy-economy-environment (EEE) models. Their coverage is detailed for energy aspects, which are usually extensively modelled in bottom-up models. Also, economic aspects treated in top-down macroeconomic models are covered in the taxonomies. Environmental aspects have the weakest coverage in the various taxonomies. Thus, classification of integrated assessment models would not be completely covered, but this is considered outside the scope of the thesis. The models used in this thesis do not go into details of environmental modeling, beyond limiting greenhouse gas emissions and assessment of energy policies with environmental goals.

As we see, some of the characteristics are used more frequently than others. Most taxonomies include the underlying *methodology* as a descriptive model characteristic, distinguishing between for example optimization, macroeconomic, econometric or accounting models. The mathematical approach is a somewhat related property, which is more specific on mathematical techniques such as linear programming, mixed integer programming or dynamic programming. Furthermore, the analytical approach (top-down versus bottom-up) is also a widely used property to characterize energy system models.

Several characteristics are necessary to describe model purpose and structure, such as geographic and sectoral coverage, time horizon and time step granulation. Then a few characteristics are needed to classify the technological detail of the energy modeling.

We see that the taxonomy given in Hall and Buckley (2016) is the broadest of the twelve examples in Table 5. In section 5.4 we have classified the models developed and used in this thesis according to the Hall and Buckley taxonomy.

5 Research focus and contributions

This section describes the focus of the thesis in relation to the methodologies described previously, classifies the models and summarizes the main scientific contributions from each of the four articles of the thesis.

5.1 Focus of the thesis

This thesis focuses on modeling of the energy system and economy modeling, assessing regional effects from energy policy and combining the bottom-up and top-down perspectives. The thesis explores effects of 1) different market assumptions, 2) improved technical modeling, 3) attaining equilibria from hard-linked large-scale models to assess greenhouse gas mitigation and 4) comparing Stackelberg versus Nash equilibria from integrated versus hard-linked models.

Figure 4 depicts the four papers of this thesis, with one paper in each quadrant. The articles are numbered going clockwise from the upper left quadrant.

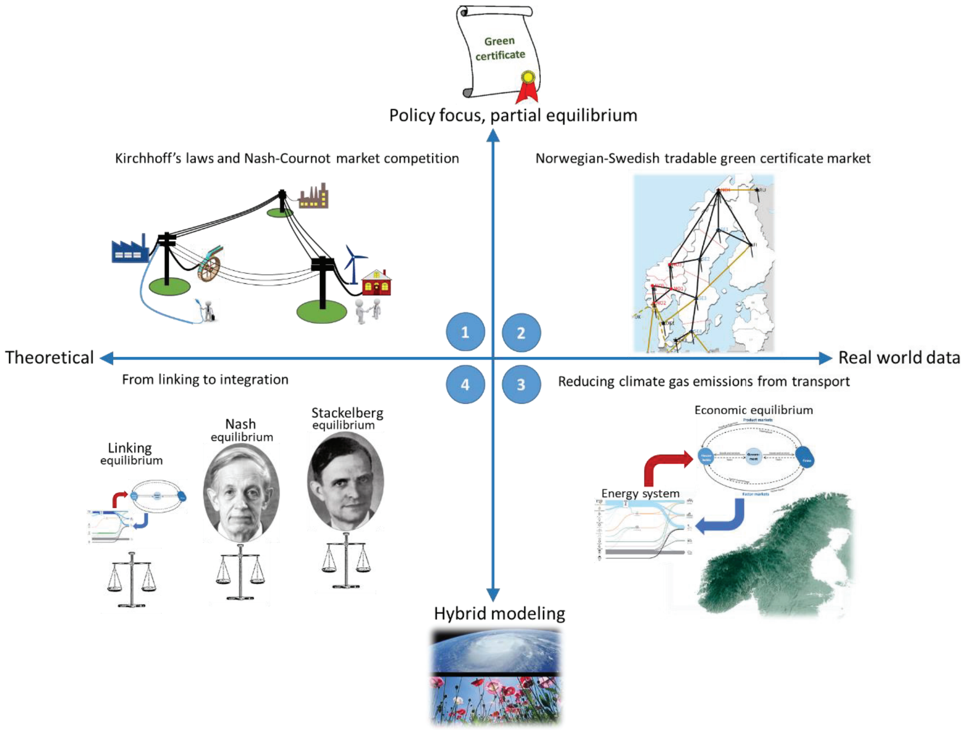

Figure 4 The papers in the thesis

As indicated in Figure 4, the first two papers use partial equilibrium models, focusing on electricity in zonal power markets. The papers assess welfare effects from introducing a tradable green certificates policy scheme. This is one of many energy policies that aim to increase renewable electricity production. Tradable green certificates are easy to implement compared with other policy instruments, since it is a market based policy scheme where the market agents decide certificate prices and locations of new renewable production. Regional effects from these policies are poorly understood. Investments in new generation capacity are highly influenced by grid bottlenecks. Efficient trade of electricity depends on the capacity of the transmission grid. Disregarding this relationship could prevent the best projects in a socio-economic cost perspective from being chosen in the market equilibrium outcome. Both papers apply a linearized DC approximation of power flows in the transmission network, imposing both Kirchhoff's current and voltage laws.

The last two papers deal with general equilibrium models, and full sectoral coverage. We extend the modeling to comprise the whole energy system (not only electricity), as well as the whole economy. These papers investigate hybrid model approaches, which allow for detailed regional policy analyses.

5.2 Choice of modeling scope in the thesis

Energy policies affect the energy system. The economy is governing the outcomes, through market behavior by economic agents. Thus, energy modeling and economy modeling are central pieces, needed for detailing regional effects of energy policy. Figure 5 shows some model related trade-offs when modeling energy policy.

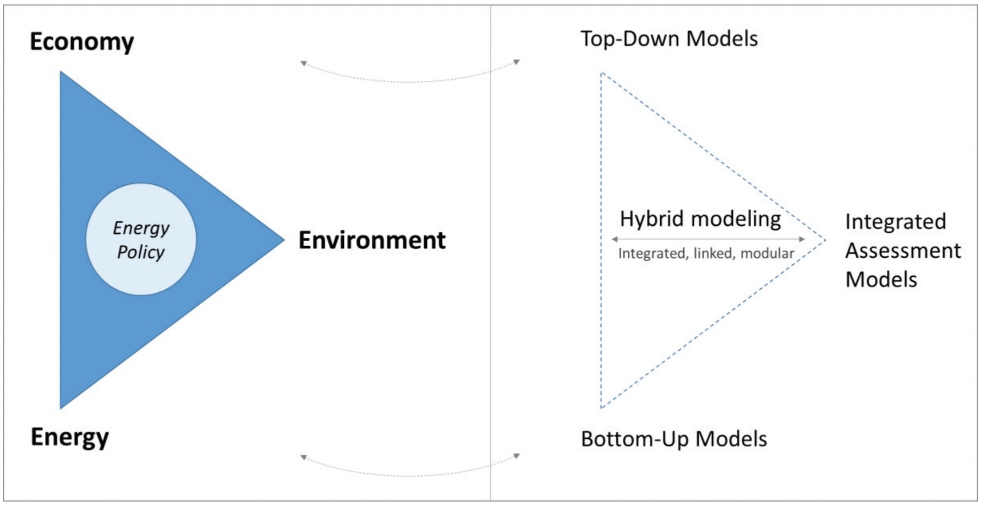

Figure 5 Energy policy modeling: Policy objectives and corresponding model coverage

Bottom-up models cover the energy system with great technological detail, while top-down models cover the economy and aggregated behavior of economic agents. Whereas hybrid models can include more or less detailed environmental modeling, they can provide normative equilibria taking into account environmental relationships. We have chosen to explore regional energy-economy aspects in depth, rather than looking at regional environmental effects. The environmental aspects in our models are represented through either the policy itself (for example green certificates), or through incorporation into the energy system model.

Integrated assessment models emphasize global environmental aspects heavier, but are less granular and provide coarser decision support assessing local regional effects of energy policy. Greenhouse gas mitigation is a global issue, and integrated assessment models are typically geographically aggregated with global coverage. This make them not so well suited for analyzing local regional effects of energy policy. Integrated assessment models are a diverse group of models as well. They are heterogenous, and contain various number of modules which are combined in many ways. Their modular design leads to more complex and subjective solution procedures based on less transparent and ambiguous assumptions, with solutions based on simulation rather than economic equilibria.

It is straightforward to extend bottom-up models with data and model coverage for greenhouse gases (or other environmental variables depending on material flows). Furthermore, CGE models are able to incorporate several key sustainability indicators in a single micro-consistent framework, allowing for systematic quantitative trade-off analysis between environmental quality, economic performance and income distribution (Böhringer & Löschel, 2006).

CGE models are also able to incorporate actor heterogeneity by introducing several types of households as well as more explicit sectors and other actors like central and local government, financial sector and various types of traders. We have utilized CGE models to grasp the economy as a whole, rather than exploring detailed behavioral aspects from heterogenous actors which is the practice of socio-technical energy transition models.

Furthermore, we focus on static and normative model equilibria, not the dynamic behavior or descriptive simulation over time. This allows us to the calculate disaggregated details necessary to assess local regional effects, instead of either running models with global coverage or models with dynamic behavior – resulting in aggregated averages and less regional details.

5.3 Research gap in hybrid modeling

The research gap for a hybrid general equilibrium approach is depicted in Figure 6. Both axes in the figure indicate increasing modeling detail, and the majority of models belong to either the x-axis (top-down economy models) or to the y-axis (bottom-up engineering energy system models). Different types of hybrid energy-economy models are represented in the figure. Top-down and bottom-up models may be coupled loosely or tightly. One rather loose way to extend the separate models is to run each model separately and exchange information from the respective solutions. This approach is termed ‘linking’, and Wene (1996) classifies model linking as either informal soft-linking (where information transfer is controlled by the user) or formal hard-linking (where information is transferred without any user judgment, usually by computer programs).

Another approach is to complement one main model with a reduced form representation of the other. This approach is exemplified in Figure 6 by the TIMES-Macro combination (a detailed energy system model with a macroeconomic module, see Kypreos and Lehtila (2015)), and the WITCH model (a neoclassical optimal growth model with a simplified energy system model, see Bosetti, Carraro, Galeotti, Massetti, and Tavoni (2006)).

The ultimate hybrid model would be a model which includes both the top-down and bottom-up aspects in one ‘integrated’ model. Such an approach was demonstrated by Böhringer and Rutherford (2008), which is indicated in Figure 6 on the 45 degree line where the engineering and the economy modeling meet each other. This approach has been developed further by several authors (Abrell & Rausch, 2016; Proença & St. Aubyn, 2013; Rausch & Mowers, 2014), but nevertheless it lacks the full detail of large-scale models.

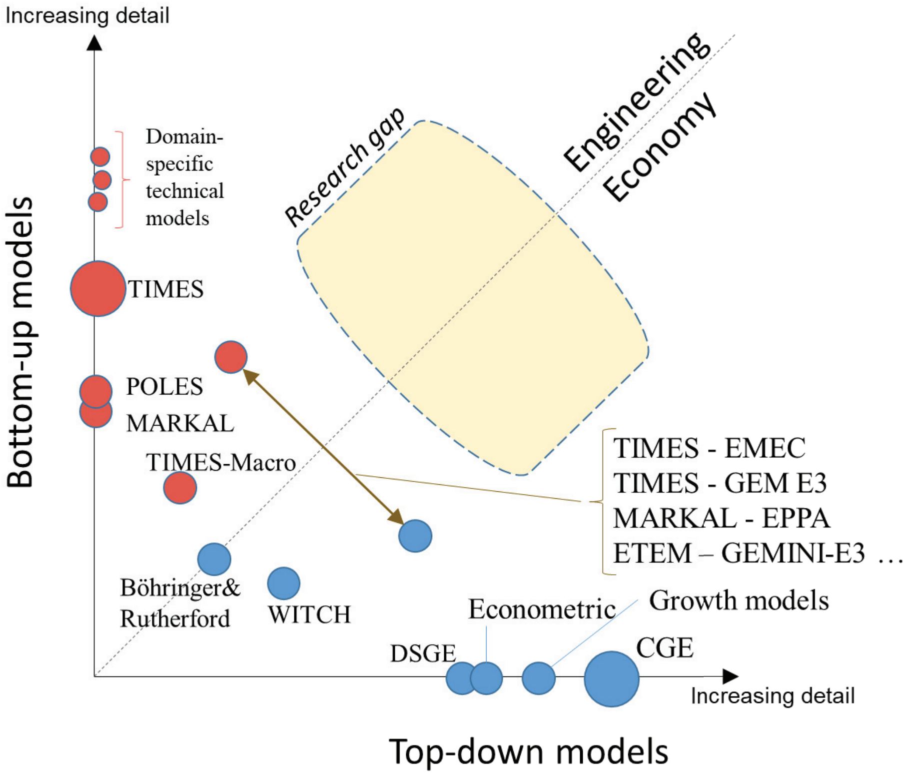

Figure 6 Research gap (based on Rodrigues (2017), Figure 1)

In this thesis we demonstrate hard-linking of large-scale top-down and bottom-up models, as well as formulation of such models into one integrated model. In paper 3 we move linked models further out along the axes, while in paper 4 we move models with more detail closer together towards the 45 degree line in Figure 6.

Paper 3 presents linking with higher detail and stronger model coupling than before. As far as we are aware, paper 3 represents the first hard-linking of large-scale stand-alone models employing a full-link with regional resolution and full-form bottom-up and top-down approach. In paper 4 we demonstrate how detailed bottom-up and top-down models can be connected tighter and solved more efficiently by combining their formulations into one integrated hybrid model.

5.4 The models of the thesis

In this section we have classified the models used in the four papers (see Table 6), using the taxonomy based on Hall and Buckley (2016) shown in Table 5.

Table 6 Classification of the models in the thesis

Hall and Buckley taxonomy **(2016)**		**Paper 1** **Helgesen and Tomasgard**	**Paper 2** **Helgesen and Tomasgard**	**Paper 3** **Helgesen, Lind, Ivanova and Tomasgard**	**Paper 4** **Helgesen and Tomasgard**
Purpose - general	*(forecasting, exploring, backcasting)*	Exploring effects of green certificates compared to business as usual scenario.	Exploring effects of green certificates compared to business as usual scenario.	Forecasting and exploring effects of regulated GHG reductions.	Forecasting
Purpose - specific	*(energy demand, energy supply, impact assessment, appraisal, environmental, integrated, modular)*	Electricity demand and supply. Impact assessment.	Electricity demand and supply. Impact assessment.	Energy demand and energy supply. Environmental regulation.	Energy demand and energy supply, integrated.
Structure of the model: internal & external assumptions	*(endogenization, non-energy sectors, end-uses, supply technologies, supply or demand)*	Exogenous demand functions. Endogenous production and prices. Perfect competition or Cournot. Kirchhoff's laws for transmission network.	Exogenous demand functions. Endogenous production and prices. Perfect competition. Kirchhoff's laws for transmission network.	Exogenous growth. Endogenous demand, production and prices. Perfect competition.	Exogenous growth, endogenous demand, production and prices. Perfect competition. Nash versus Stackelberg equilibrium.
The analytical approach	*(top-down, bottom-up, hybrid, other)*	Bottom-up	Bottom-up	Bottom-up and top-down, hard-linked.	Bottom-up and top-down, hard-linked and integrated.
The underlying methodology	*(econometric, macroeconomic, microeconomic, economic equilibrium, optimization, simulation, stochastic/Monte-Carlo, spatial, multi-criteria, accounting)*	Partial economic equilibrium where each agent optimizes own behavior.	Partial economic equilibrium where each agent optimizes own behavior.	General economic equilibrium where each agent optimizes own behavior. Macroeconomic statistical data in CGE model based on microeconomic foundation. Optimization of energy system.	General economic equilibrium where each agent optimizes own behavior. Optimization of energy system.
The mathematical approach	*(linear programming, mixed-integer programming, dynamic programming, fuzzy logic, agent-based programming)*	Complementarity (multi player optimization).	Complementarity (multi player optimization).	Linear programming and complementarity.	Linear programming, complementarity and Stackelberg first mover.
Geographical coverage	*(global, regional, national, local, single-project)*	General spatial model, local/national/regional (3 regions).	Regional, spatial (9 regions).	National, spatial (5 regions).	General one-region model.
Sectoral coverage	*(energy sectors, other specific sectors, overall economy)*	Aggregated electricity demand.	Aggregated electricity demand.	Overall economy, 36 economic sectors, 81 energy service demand groups.	Overall economy, 4 economic sectors, 2 energy service demand groups.
The time horizon	*(short, medium, long-term)*	Short term	Medium term	Long term	Medium term
Data requirements	*(qualitative, quantitative, monetary, aggregated, disaggregated)*	Quantitative, disaggregated.	Quantitative, disaggregated.	Quantitative, disaggregated. National accounts and energy balance. Technical parameters, demand and substitution elasticities.	Quantitative, disaggregated. National accounts and energy balance. Technical parameters, demand and substitution elasticities.
The time step	*(minutely, hourly, monthly, yearly, five-yearly, user-defined)*	Static (user defined comparative static)	Static (user defined comparative static)	Energy system: user-defined (five-yearly). Economic: comparative static.	Energy system: user-defined (yearly). Economic: comparative static.
Renewable technology inclusion	*(hydro, solar pv, solar thermal, geothermal, wind, wave, biomass, tidal)*	User defined	User defined	User defined	User defined
Storage technology inclusion	*(pumped hydro, battery, compressed-air, hydrogen)*	n.a.	n.a.	User defined	n.a.
Demand characteristic inclusion - transport, residential, commercial, agricultural	*(transport, residential, commercial, agricultural)*	aggregated	aggregated	user defined	user defined
Cost inclusion	*(fuel prices, fuel handling, investment, fixed operation & maintenance, variable operation & maintenance, co2)*	Combination of exogenous parameters and endogenous calculation.	Combination of exogenous parameters and endogenous calculation.	Combination of exogenous parameters and endogenous calculation.	Combination of exogenous parameters and endogenous calculation.

The taxonomy is quite extensive, and the classifications provide a useful picture of the various models and their characteristics.

5.5 Article contributions and statements

In this section we describe the four articles in the thesis. The articles follow in Part two.

5.5.1 An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's Laws and Nash-Cournot competition

The first paper is theoretical, and the main contribution is to combine a public support scheme for electricity production with a power market model in which strategic generators compete and exercise market power in a capacitated transmission network with spatial energy exchange. It extends a seminal paper from Hobbs (2001) by including a tradable green certificate policy scheme. We include imperfect competition among suppliers and assume linear demand functions. We employ complementarity modeling to calculate economic equilibria before and after the policy is incurred, thus using a comparative statics method without studying dynamics of intermediate market solutions.

Policy instruments constitute interference to the market, and will inevitably lead to deadweight losses. The paper shows welfare effects of energy policy with tree alternative types of market competition: 1) Cournot competition, 2) Cournot competition with arbitragers and 3) Perfect competition. To our knowledge, this is the first model that combines an approximation of the AC transmission network with equilibrium modeling of support schemes and in addition allows imperfect competition.

The paper employs a stylized example, and shows that green certificates incur large deadweight losses. The distribution of welfare effects depends heavily on both market competition and transmission network bottlenecks. Since we address imperfect competition, we are able to demonstrate partial welfare gains from the instrument due to reduced market power and thus increased competition. When new firms enter in a market with imperfect competition, consumers in general gain from the certificate scheme. New firms increase the market competition since they increase their profits from renewable generation more than existing Cournot players do. Existing firms choose not to generate renewable electricity, since they want to hold back production and keep prices as high as possible. If there are barriers to new entrants, then partial equilibrium welfare losses affect both firms and consumers – unless the market has perfect competition, in which case consumers must cover the full cost of the certificate scheme (including deadweight losses).

The results provide decision makers with improved insight when they evaluate which policy instruments should be employed to reach political goals. The paper shows that a diversity of effects may follow from a market based policy scheme such as the tradable green certificates. The paper shows that existing firms are likely to bear most of the deadweight losses from the support scheme, and that regional differences may be substantial, depending on transmission grid bottlenecks.

The article has been published in Energy Economics (Elsevier). Co-author is my supervisor, Professor Asgeir Tomasgard. The research topic was initiated in the project Regional Effects of Energy Policy. The modelling approach was outlined through discussions between me and Professor Tomasgard. I collected data, formulated and implemented the model. I ran the simulations. Interpretation of the results was done in collaboration with Professor Tomasgard. I am the main author of the manuscript.

5.5.2 Efficiency and welfare distribution effects from the Norwegian-Swedish tradable green certificates market

The second paper deals with the common Norwegian-Swedish tradable green certificate market. The model assumes perfect competition, but handles nonlinear electricity demand functions which we assume to have constant own-price elasticity. Compared with the model in the previous paper, it processes much more information due to more geographical regions, technologies, time-steps and transmission network data. Three years of hourly consumption and price data from regional electricity markets are utilized to characterize the local electricity markets during season and day/night. An equilibrium model is developed and run to inspect market outcomes when the tradable green certificate scheme is introduced. A future scenario which include planned transmission investments is defined. A further scenario where local demand increase in addition to expanded transmission capacities is also defined. Welfare effects for old producers, new producers and consumers are calculated per region, as well as for the transmission system operator. The combined deadweight loss is calculated for each scenario.

Main conclusions: Increased supply of electricity leads to large welfare transfers. An unbalanced stimulation of the supply side produces substantial deadweight losses from the scheme. In order to reduce deadweight losses new supply should be combined with a) increased transmission capacities providing better market coupling or b) increased local demand. Localization of new renewable electricity production depends heavily on transmission behavior, and this affects the efficiency of the scheme. Regional prices may differ and produce large differences in welfare effects. This affects the national outcomes of the common Norwegian-Swedish tradable green certificate market, as well as the local outcomes for consumers and old producers. Densely populated regions have large deviations in net social welfare. Regional losers in scenarios with high export (introduction of the scheme and new cross-country cables towards North-European markets) turn into regional winners if local demand increase. Local resources are best exploited by an efficient grid, resulting in lower deadweight losses. Regional welfare differences are also evened out by an efficient grid with sufficient capacity. These benefits must be balanced against the costs of grid improvements.

The research provides insights to firms who want to understand the consequences of the tradable certificate market, and for policy makers who shall construct new energy policies. If there is not a demand for new electricity supply, old producers will experience large profit losses, and the overall deadweight losses turn the net social welfare effect negative. This may still be beneficial through crowding out fossil electricity production, but that is not the case in Norway and Sweden. Planned cables providing improved cross-border market coupling is an essential companion to the green certificates. Stimulation towards local use of the increased supply provides the best outcome, measured by net social welfare. If regional differences should be avoided, then the costs of grid capacity expansions need to be taken into account when evaluating potential energy policies.

The article has been submitted to an international peer-reviewed journal. Co-author is my supervisor, Professor Asgeir Tomasgard. The research topic was initiated in the project Regional Effects of Energy Policy. The modelling approach was outlined through discussions between me and Professor Tomasgard. I collected data, formulated and implemented the model and had discussions with TrønderEnergi. I ran the simulations. Interpretation of the results was done in collaboration with Professor Tomasgard. I am the main author of the manuscript.

5.5.3 Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport

The third paper analyzes how reduced climate gas emissions from transport could be achieved, and which regional effects that could be expected. The paper demonstrates hard-linking of a large-scale computable general equilibrium (CGE) model of the Norwegian economy and a large-scale TIMES model of the Norwegian energy system. Both models are divided in 5 regions equal to the electricity price zones of Norway, and the models are linked together by interchanging solutions: A solution from one model is utilized as input to the other model, and this linking is executed without user input, representing a hard-linked approach. The approach is 'full-form', i.e. the bottom-up model covers extensive technology data and the top-down model includes a disaggregated economic structure. The linking is done across all sectors, demonstrating a 'full-link' approach.

Our first contribution is to pursue a hard-linked, full-link, full-form approach, filling a knowledge gap between current state of the art practices. As far as we are aware, the article represents the first hard-linking of large-scale stand-alone models employing a full-link with regional resolution and full-form bottom-up and top-down approach.

Convergence characteristics of full-link, full-form models have been poorly investigated. Our approach eliminates two important drawbacks of soft-linked models: They are time and labor consuming to run, so convergence may not be tested stringently. Current state-of-the art articles have reported few iteration cycles, and have also reported convergence problems. Whether full-link full-form models are able to reach convergence, represents a knowledge gap. Our second contribution is therefore to utilize our hard-linked approach to check whether we are able to reach convergence using a full-link full-form approach. We demonstrate that the approach produces steady convergence towards a general equilibrium.

Our third contribution is related to the case study, which is of high importance for Norwegian policy makers. While a 50% reduction of emissions from transport has been widely suggested by policy makers as a tool to meet Norwegian climate obligations, the feasibility and welfare effects has not been studied in the literature as far as we know. Our finding is that greenhouse gas emissions from transport in 2030 may be halved compared to a business-as-usual scenario, and halving the emissions amounts to a 6.5% income reduction. The regional utility reductions translate to between 6.1% and 7.4% reduction of income.

The research provides insights into the cost levels needed to mitigate greenhouse gas emissions from transport. The study shows where new technologies are likely to have effects in the market, and might indicate appropriate sectors for authorities to facilitate technology development. The linking approach demonstrates that the ability to take feedback and adjust solutions have big effects on the costs, and suggest that policy instruments on the demand side affecting demand behavior should be further pursued.

The article has been published in Energy – The International Journal (Elsevier). Co-authors are Dr. Arne Lind, my co-supervisor Dr. Olga Ivanova and my supervisor, Professor Asgeir Tomasgard. The research topic and the CGE modeling was initiated in the project Regional Effects of Energy Policy, in close collaboration with Dr. Ivanova. I collected data in collaboration with Dr. Ivanova and Dr. Lind. The modeling approach was outlined through discussions between me, Dr. Lind and Dr. Ivanova. I formulated and implemented the hybrid linking approach. I ran the simulations. Interpretation of the results was done in collaboration with Dr. Lind and Professor Tomasgard. I am the main author of the manuscript.

5.5.4 From linking to integration of energy system models and computational general equilibrium models – Effects on equilibria and convergence

The fourth paper compares hybrid approaches of hard-linking and integration. The model linking is taken one step further, and we demonstrate *integration* of a CGE model and an energy system model into one larger complete model. We combine the top-down and bottom-up models using complementarity formulations and optimization formulations. Model integration is implemented in two different model setups (MCP or NLP), while model linking is implemented in four different hard-linked setups. The main contribution is to integrate full-linked hybrid models and compare with hard-linked approaches. The authors are not aware of previous work that investigates such comparison.

In the four linking configurations, a solution is found by iterating between the two models until convergence is reached. The same equilibrium solution is found by all hard-linked setups in all problem instances. Next, an integrated MCP model is introduced by extending the computable general equilibrium mixed complementarity model with the Karush-Kuhn-Tucker conditions that represent the bottom-up linear programming model. The solution from this model constitutes a Nash equilibrium, where each player knows the optimal reaction from the other players, decisions are made simultaneously and no player has an incentive to change his response. Furthermore, the 'link-equilibrium' from all the hard-linked models is identical to the Nash equilibrium from the integrated MCP implementation. Separate top-down and bottom-up models contain different domain knowledge. It is a natural step to couple these models by iterating towards a common solution. Our findings confirm that such iterations may converge to a Nash equilibrium, thus providing methodological support for model linking.

An alternative integrated NLP model is provided, where the bottom-up model objective is optimized while the top-down model is included as additional constraints. In some problem instances this integrated NLP model finds a different solution. This nonlinear program corresponds to a multi-follower bilevel formulation, with the energy system model as the leader and the general equilibrium players (firms and household) as followers. The solution from this model constitutes a Stackelberg equilibrium. The Stackelberg equilibrium from this bilevel formulation pareto-dominates the Nash equilibrium from the other model setups in some problem instances, and is identical to the Nash equilibrium in the remaining problem instances. The different ways to couple the mathematical models represents different real-world situations, and may therefore naturally result in different equilibria.

The demonstrated integration between the energy system and the whole economy can be implemented across all sectors (full-link). Thus, existing data and model expertise could be utilized efficiently, also pursuing model integration. Integrating two models into one creates a larger and more complex model, with the risk of increased solver time. Our results show that the larger integrated models solve much faster than the hard-linked models. The integrated models are larger but avoid time-consuming iterations, and may therefore be faster. This is encouraging, and indicates that higher hybrid modeling ambitions may be reached, possibly permitting larger and more complex integrated models to be solved than previously expected.

The article has been published in Energy – The International Journal (Elsevier). Co-author is my supervisor, Professor Asgeir Tomasgard. The research topic was initiated in the project Regional Effects of Energy Policy. I collected data, formulated and implemented the models and implemented the different hybrid approaches. I ran the simulations. Interpretation of the results was done in collaboration with Professor Tomasgard. I am the main author of the manuscript.

5.5.5 Other contributions

In addition to the four articles, the doctoral work has contributed to two book chapters in Giannakidis et al. (2015): Lecture Notes in Energy, volume 30, *Informing Energy and Climate Policies Using Energy Systems Models - Insights from Scenario Analysis Increasing the Evidence Base*. The chapters describe hybrid energy-economy model coupling. In a climate constrained future, hybrid energy-economy model coupling gives additional insight into interregional competition, trade, industrial delocalisation and overall macroeconomic consequences of decarbonising the energy system.

Chapter 19 is called *Economic Impacts of Future Changes in the Energy System — Global Perspectives* (Glynn et al., 2015a). The chapter summarises modelling methodologies developed in the ETSAP community to assess economic impacts of decarbonising energy systems at a global level. I am a co-author of the manuscript. The main author is James Glynn. 18 ETSAP colleagues co-authored the manuscript. The chapter has been published in Lecture Notes in Energy, Volume 30, Chapter 19 (Springer).

Chapter 20 is called *Economic Impacts of Future Changes in the Energy System — National Perspectives* (Glynn et al., 2015b). The chapter outlines modelling studies which show that burden sharing rules and national revenue recycling schemes for carbon tax are critical for the long-term viability of economic growth and equitable engagement on combating climate change. I am a co-author of the manuscript. The main author is James Glynn. 18 ETSAP colleagues co-authored the manuscript. The chapter has been published in Lecture Notes in Energy, Volume 30, Chapter 20 (Springer).

References

Abrell, J., & Rausch, S. (2016). Cross-country electricity trade, renewable energy and European transmission infrastructure policy. *Journal of Environmental Economics and Management, 79*, 87-113. doi:10.1016/j.jeem.2016.04.001

Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., & Schulze, K. (2005). Changes in Nature's Balance Sheet: Model-based Estimates of Future Worldwide Ecosystem Services. *Ecology and Society, 10*(2).

Amundsen, E. S., & Bergman, L. (2007). Integration of multiple national markets for electricity: The case of Norway and Sweden. *Energy Policy, 35*(6), 3383-3394. doi:http://dx.doi.org/10.1016/j.enpol.2006.12.014

Amundsen, E. S., & Bergman, L. (2012). Green Certificates and Market Power on the Nordic Power Market. *Energy Journal, 33*(2), 101-117. doi:10.5547/01956574.33.2.5

Arrow, K. J., & Debreu, G. (1954). EXISTENCE OF AN EQUILIBRIUM FOR A COMPETITIVE ECONOMY. *Econometrica, 22*(3), 265-290. doi:10.2307/1907353

Balabanov, T. (2011). Overview and evaluation of models in use for M/A policy portfolios and selection the relevant for Promitheas-4. http://www.fim.edu.al/promitheas-4/pdf/Climate_Mitigation_Adaptation_4_Zgjedhja_e_Modelit.pdf.

Bernow, S., Rudkevich, A., Ruth, M., & Peters, I. (1998). *A Pragmatic CGE Model for Assessing the Influence of Model Structure and Assumptions in Climate Change Policy Analysis* (96-190). Retrieved from Boston: http://www.tellus.org/pub/A%20Pragmatic%20CGE%20Model%20for%20Assessing%20the%20Influence%20of%20Model%20Structure%20and%20Assumptions%20in%20Climate%20Change%20Policy%20Analysis.pdf

Bishop, J. D. (1995). Adam Smith's Invisible Hand Argument. *Journal of Business Ethics, 14*(3), 165-180.

Bithas, K. P., & Christofakis, M. (2006). Environmentally sustainable cities. Critical review and operational conditions. *Sustainable Development, 14*(3), 177-189. doi:10.1002/sd.262

Bjerkan, K. Y., Nørbech, T. E., & Nordtømme, M. E. (2016). Incentives for promoting Battery Electric Vehicle (BEV) adoption in Norway. *Transportation Research Part D: Transport and Environment, 43*, 169-180. doi:http://dx.doi.org/10.1016/j.trd.2015.12.002

Borenstein, S., & Bushnell, J. (1999). An empirical analysis of the potential for market power in California's electricity industry. *Journal of Industrial Economics, 47*(3), 285-323.

Borenstein, S., Bushnell, J., Kahn, E., & Stoft, S. (1995). Market power in California electricity markets. *Utilities Policy, 5*(3), 219-236.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., . . . Galli, A. (2013). Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. *Ecological*

Indicators, 24(Supplement C), 518-533. doi:https://doi.org/10.1016/j.ecolind.2012.08.005

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., & Tavoni, M. (2006). WITCH - A World Induced Technical Change Hybrid model. *Energy Journal*, 13-37.

Bruvoll, A. (2009). On the measurement of environmental taxes. *Discussion Papers,* (599), 22. Retrieved from http://www.ssb.no/a/publikasjoner/pdf/DP/dp599.pdf

Bushnell, J. (2003). A mixed complementarity model of hydrothermal electricity competition in the western United States. *Operations Research, 51*(1), 80-93. doi:10.1287/opre.51.1.80.12800

Bushnell, J. B., Mansur, E. T., & Saravia, C. (2008). Vertical arrangements, market structure, and competition: An analysis of restructured US electricity markets. *American Economic Review, 98*(1), 237-266. doi:10.1257/aer.98.1.237

Bye, T., & Hope, E. (2007). Deregulering av elektrisitetsmarkedet: Norske erfaringer (Deregulation of the electricity market: Norwegian experiences). [Deregulating electricity markets - Norwegian experiences]. *Økonomisk forum, 61*(1), 17-25.

Böhringer, C., Koschel, H., & Moslener, U. (2008). Efficiency losses from overlapping regulation of EU carbon emissions. *Journal of Regulatory Economics, 33*(3), 299-317. doi:10.1007/s11149-007-9054-8

Böhringer, C., & Löschel, A. (2006). Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. *Ecological Economics, 60*(1), 49-64. doi:10.1016/j.ecolecon.2006.03.006

Böhringer, C., & Rosendahl, K. E. (2010). Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *Journal of Regulatory Economics, 37*(3), 316-325. doi:10.1007/s11149-010-9116-1

Böhringer, C., Rutherford, T., & Wiegard, W. (2003). Computable General Equilibrium Analysis: Opening a Black Box, 38. Retrieved from ftp://ftp.zew.de/pub/zew-docs/dp/dp0356.pdf

Böhringer, C., & Rutherford, T. F. (2008). Combining bottom-up and top-down. *Energy Economics, 30*(2), 574-596. doi:10.1016/j.eneco.2007.03.004

Böhringer, C., & Rutherford, T. F. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. *Journal of Economic Dynamics & Control, 33*(9), 1648-1661. doi:10.1016/j.jedc.2008.12.007

Böhringer, C., Rutherford, T. F., & Wiegard, W. (2003). Computable general equilibrium analysis: Opening a black box, 34. Retrieved from ftp://ftp.zew.de/pub/zew-docs/dp/dp0356.pdf

C2ES. (2017). Global Emissions. Retrieved 2018-02-04 from https://www.c2es.org/content/international-emissions/

CAFE. (2004). *Assessment of the Effectiveness of European Air Quality Policies and Measures. Case study 1 - Comparison of the EU and US Approaches Towards Acidification, Eutrophication and Ground Level Ozone*. Retrieved from Brussels: http://ec.europa.eu/environment/archives/cafe/activities/pdf/case_study1.pdf

Clarke, L., Weyant, J., & Edmonds, J. (2008). On the sources of technological change: What do the models assume? *Energy Economics, 30*(2), 409-424. doi:https://doi.org/10.1016/j.eneco.2006.05.023

Coase, R. H. (1960). The Problem of Social Cost. *The Journal of Law & Economics, 3*, 1-44.

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy, 87*(4), 1059-1082. doi:10.1016/j.apenergy.2009.09.026

Dahlan, N. Y., & Kirschen, D. S. (2012). An Empirical Approach of Modelling Electricity Prices in an Oligopoly Market. *2012 Ieee International Conference on Power and Energy (Pecon)*, 256-261.

DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., . . . Zeyringer, M. (2017). Formalizing best practice for energy system optimization modelling. *Applied Energy, 194*, 184-198. doi:https://doi.org/10.1016/j.apenergy.2017.03.001

Denny, K., Hannan, A., & O'Rourke, K. (1997). *Fiscal increasing Returns, Unemployment and Multiple Equilibria: Evidence from a Computable General Equilibrium Model*. University College Dublin. Ireland.

Dierker, E. (1972). Two Remarks on the Number of Equilibria of an Economy. *Econometrica, 40*(5), 951-953. doi:10.2307/1912091

Dincer, I. (2002). The role of exergy in energy policy making. *Energy Policy, 30*(2), 137-149. doi:10.1016/S0301-4215(01)00079-9

Dixon, P. B., & Jorgenson, D. W. (2013). *Handbook of Computable General Equilibrium Modeling* (P. B. Dixon & D. W. Jorgenson Eds. Vol. 1A): North Holland.

Energy 2020: A strategy for competitive, sustainable and secure energy, (2010).

EC. (2018). Energy Strategy and Energy Union. *European Commission policies, information and services.* Retrieved 2018-01-03 from https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union

EU Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, (2009).

EU. (2018). Energy in EU. *EU by topic.* Retrieved 2018-01-01 from https://europa.eu/european-union/topics/energy_en

Figenbaum, E., Assum, T., & Kolbenstvedt, M. (2015). Electromobility in Norway: Experiences and Opportunities. *Research in Transportation Economics, 50*, 29-38. doi:10.1016/j.retrec.2015.06.004

Fleiter, T., Worrell, E., & Eichhammer, W. (2011). Barriers to energy efficiency in industrial bottom-up energy demand models-A review. *Renewable & Sustainable Energy Reviews, 15*(6), 3099-3111. doi:10.1016/j.rser.2011.03.025

Fortes, P., Pereira, R., Pereira, A., & Seixas, J. (2014). Integrated technological-economic modeling platform for energy and climate policy analysis. *Energy, 73*, 716-730. doi:http://dx.doi.org/10.1016/j.energy.2014.06.075

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy, 52*, 10-24. doi:https://doi.org/10.1016/j.enpol.2012.04.001

Giannakidis, G., Labriet, M., ÓGallachóir, B., & Tosato, G. (2015). *Informing energy and climate policies using energy systems models. Insights from scenario analysis increasing the evidence base.* (Vol. 30): Springer International Publishing, Switzerland. doi.

Gillett, N. P., Arora, V. K., Matthews, D., & Allen, M. R. (2013). Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. *Journal of Climate, 26*(18), 6844-6858. doi:10.1175/jcli-d-12-00476.1

Gillingham, K., & Palmer, K. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy, 8*(1), 18-38. doi:10.1093/reep/ret021

Global Footprint Network. (2017a). Earth Overshoot Day. Retrieved 2017-12-21 from www.overshootday.org

Global Footprint Network. (2017b). Ecological Footprint (Number of Earths). Retrieved 2017-12-21 from http://data.footprintnetwork.org/#/countryTrends?type=earth&cn=5001

Glynn, J., Fortes, P., Krook-Riekkola, A., Labriet, M., Vielle, M., Kypreos, S., . . . ÓGallachóir, B. P. (2015a). Economic Impacts of Future Changes in the Energy

System — Global Perspectives. In G. Giannakidis, M. Labriet, B. P. ÓGallachóir, & G. Tosato (Eds.), *Informing Energy and Climate Policies Using Energy Systems Models* (pp. 26): Springer International Publishing.

Glynn, J., Fortes, P., Krook-Riekkola, A., Labriet, M., Vielle, M., Kypreos, S., . . . ÓGallachóir, B. P. (2015b). Economic Impacts of Future Changes in the Energy System — National Perspectives. In G. Giannakidis, M. Labriet, B. P. ÓGallachóir, & G. Tosato (Eds.), *Informing Energy and Climate Policies Using Energy Systems Models* (pp. 30): Springer International Publishing.

Grubb, M., Edmonds, J., ten Brink, P., & Morrison, M. (1993). The costs of limiting fossil-fuel CO2 emissions: A Survey and Analysis. *Annual Review of Energy and the Environment, 18*, pp. 397-478.

Grubb, M., Hourcade, J.-C., & Neuhoff, K. (2015). The Three Domains structure of energy-climate transitions. *Technological Forecasting and Social Change, 98*(Supplement C), 290-302. doi:https://doi.org/10.1016/j.techfore.2015.05.009

Hall, L. M. H., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy, 169*(Supplement C), 607-628. doi:https://doi.org/10.1016/j.apenergy.2016.02.044

Helgesen, P. I., Lind, A., Ivanova, O., & Tomasgard, A. (2018). Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport. *Energy*. doi:https://doi.org/10.1016/j.energy.2018.05.005

Herbst, A., Reitze, F., Toro, F. A., & Jochem, E. (2012). *Bridging macroeconomic and bottom up energy models - the case of efficiency in industry*. Paper presented at the ECEEE 2012 Industrial Summer Study, Arnhem, The Netherlands.

Hermann, W. A. (2006). Quantifying global exergy resources. *Energy, 31*(12), 1685-1702. doi:https://doi.org/10.1016/j.energy.2005.09.006

Hobbs, B. F. (2001). Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. *Ieee Transactions on Power Systems, 16*(2), 194-202. doi:10.1109/59.918286

Hoffman, E., & Spitzer, M. L. (1982). The Coase Theorem: Some Experimental Tests. *The Journal of Law and Economics, 25*(1), 73-98. doi:10.1086/467008

Hourcade, J.-C., Richels, R., Robinson, J., Chandler, W., Davidson, O., Edmonds, J., . . . Tudini, A. (1996). Estimating the Costs of Mitigating Greenhouse Gases. In J. P. Bruce, H. Lee, & E. F. Haites (Eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change* (pp. 259-290). Cambridge: Cambridge University Press.

Hourcade, J. C., Jaccard, M., Bataille, C., & Ghersi, F. (2006). Hybrid modeling: New answers to old challenges - Introduction to the special issue of The Energy Journal. *Energy Journal*, 1-11.

Hughes, N., & Strachan, N. (2010). Methodological review of UK and international low carbon scenarios. *Energy Policy, 38*(10), 6056-6065. doi:https://doi.org/10.1016/j.enpol.2010.05.061

Huppmann, D., & Egging, R. (2014). Market power, fuel substitution and infrastructure – A large-scale equilibrium model of global energy markets. *Energy, 75*, 483-500. doi:https://doi.org/10.1016/j.energy.2014.08.004

IEA. (2017a). *CO2 emissions from fuel combustion*. Retrieved from https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf

IEA. (2017b). *Energy Technology Perspectives 2017*. Retrieved from Paris:

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Geneva, Switzerland:

Jaffe, A. B., & Stavins, R. N. (1994). The energy-efficiency gap What does it mean? *Energy Policy, 22*(10), 804-810. doi:https://doi.org/10.1016/0301-4215(94)90138-4

Jaffe, A. B., & Stavins, R. N. (1995). Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion. *Journal of Environmental Economics and Management, 29*(3), S43-S63. doi:https://doi.org/10.1006/jeem.1995.1060

Jebaraj, S., & Iniyan, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews, 10*(4), 281-311. doi:https://doi.org/10.1016/j.rser.2004.09.004

Johansen, L. (1960). *A Multi-Sector Study of Economic Growth*: North-Holland Publishing Company, Amsterdam, Netherlands.

Kehoe, T. J. (1985). Multiplicity of Equilibria and Comparative Statics*. *The Quarterly Journal of Economics, 100*(1), 119-147. doi:10.2307/1885738

Kehoe, T. J. (1991). Computation and Multiplicity of Equilibria. In W. Hildenbrand & H. Sonnenschein (Eds.), *Handbook of Mathematical Economics* (Vol. 4, pp. 2051-2144): Elsevier Science Publishers BV.

Kehoe, T. J. (1998). Uniqueness and Stability. In A. P. Kirman (Ed.), *Elements of General Equilibrium Analysis* (pp. 38–87): Wiley-Blackwell.

KLD. (2014, 2014-12-12). The agreement on climate policy. Retrieved 2018-07-04 from https://www.regjeringen.no/en/topics/climate-and-environment/climate/innsiktsartikler-klima/agreement-on-climate-policy/id2076645/

KLD. (2017a). *Climate strategy for 2030 - restructuring Norway in European cooperation (Meld. St. 41 2016-2017)*. (41). Oslo Retrieved from https://www.regjeringen.no/contentassets/7d3c209f821248da8d4727713ab9619c/no/pdfs/stm201620170041000dddpdfs.pdf.

Lov om klimamål (klimaloven) - Law on climate targets, (2017b).

Krey, V., Masera, O., Blanford, G., Bruckner, T., Cooke, R., Fisher-Vanden, K., . . . Zwickel, T. (2014). *Annex II: Metrics & Methodology. In:Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Cambridge and New York: https://www.ipcc.ch/report/ar5/

Kypreos, S., & Lehtila, A. (2015). Decomposing TIAM-MACRO to Assess Climatic Change Mitigation. *Environmental Modeling & Assessment, 20*(6), 571-581. doi:10.1007/s10666-015-9451-9

Lanz, B., & Rausch, S. (2011). General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis. *Energy Economics, 33*(5), 1035-1047. doi:10.1016/j.eneco.2011.06.003

Li, F. G. N., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions, 24*, 106-129. doi:https://doi.org/10.1016/j.eist.2016.08.002

Li, F. G. N., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change, 100*, 290-305. doi:https://doi.org/10.1016/j.techfore.2015.07.017

Lipsey, R. G., & Lancaster, K. (1956). The General Theory of Second Best. *The Review of Economic Studies, 24*(1), 11-32. doi:10.2307/2296233

Lucas, R. E. (1976). ECONOMETRIC POLICY EVALUATION - CRITIQUE. *Carnegie-Rochester Conference Series on Public Policy, 1*, 19-46. doi:10.1016/s0167-2231(76)80003-6

Mas-Colell, A. (1991). On the Uniqueness of Equilibrium Once Again. In W. A. Barnett, B. Cornet, C. D'Aspremont, & A. Mas-Colell (Eds.), *Equilibrium Theory and*

Applications: Proceedings of the Sixth International Symposium in Economic Theory and Econometrics: Cambridge University Press.

Mathiesen, L. (1985). COMPUTATIONAL EXPERIENCE IN SOLVING EQUILIBRIUM-MODELS BY A SEQUENCE OF LINEAR COMPLEMENTARITY-PROBLEMS. *Operations Research, 33*(6), 1225-1250. doi:10.1287/opre.33.6.1225

Mathiesen, L. (1987). AN ALGORITHM BASED ON A SEQUENCE OF LINEAR COMPLEMENTARITY-PROBLEMS APPLIED TO A WALRASIAN EQUILIBRIUM-MODEL - AN EXAMPLE. *Mathematical Programming, 37*(1), 1-18. doi:10.1007/bf02591680

Mazzucato, M. (2013). *The Entrepreneurial State - Debunking Public vs. Private Sector Myths*: Anthem Press.

McBain, B., Lenzen, M., Wackernagel, M., & Albrecht, G. (2017). How long can global ecological overshoot last? *Global and Planetary Change, 155*(Supplement C), 13-19. doi:https://doi.org/10.1016/j.gloplacha.2017.06.002

Menz, F. C., & Seip, H. M. (2004). Acid rain in Europe and the United States: an update. *Environmental Science & Policy, 7*(4), 253-265. doi:https://doi.org/10.1016/j.envsci.2004.05.005

Mercenier, J. (1995). NONUNIQUENESS OF SOLUTIONS IN APPLIED GENERAL EQUILIBRIUM-MODELS WITH SCALE ECONOMIES AND IMPERFECT COMPETITION. *Economic Theory, 6*(1), 161-177. doi:10.1007/bf01213945

Milford, R. L., Pauliuk, S., Allwood, J. M., & Müller, D. B. (2013). The Roles of Energy and Material Efficiency in Meeting Steel Industry CO2 Targets. *Environmental Science & Technology, 47*(7), 3455-3462. doi:10.1021/es3031424

Mirza, F. M., & Bergland, O. (2015). Market Power in the Norwegian Electricity Market: Are the Transmission Bottlenecks Truly Exogenous? *Energy Journal, 36*(4), 313-330. doi:10.5547/01956574.36.4.fmir

Nakata, T. (2004). Energy-economic models and the environment. *Progress in Energy and Combustion Science, 30*(4), 417-475. doi:https://doi.org/10.1016/j.pecs.2004.03.001

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. *Progress in Energy and Combustion Science, 37*(4), 462-502. doi:https://doi.org/10.1016/j.pecs.2010.08.001

Nakicenovic, N., Grübler, A., Gaffin, S., Jung, T. T., Kram, T., Morita, T., . . . Victor, N. (2003). IPCC Sres Revisited: A Response. *Energy & Environment, 14*(2), 187-214. doi:10.1260/095830503765184592

Neuhoff, K. (2003). *Integrating Transmission and Energy Markets Mitigates Market Power*. DAE Working Paper Series. Department of Applied Economics. University of Cambridge. Retrieved from http://www.econ.cam.ac.uk/electricity/publications/wp/ep17.pdf

NOU. (2012). *Norwegian Official Report 2012:9 Energy green paper - value creation, security of supply and environment*. Retrieved from Oslo:

NOU. (2015). *Norwegian Official Report 2015:15 Environmental Pricing - Report from a Green Tax Commission*. Retrieved from Oslo: https://www.regjeringen.no/en/dokumenter/nou-2015-15/id2465882/

OECD. (2011). Interactions Between Emission Trading Systems and Other Overlapping Policy Instruments. Retrieved from http://www.oecd.org/env/tools-evaluation/Interactions%20between%20Emission%20Trading%20Systems%20and%20Other%20Overlapping%20Policy%20Instruments.pdf

OFV. (2018). Car sales in 2017. Retrieved 2018-06-03 from http://www.ofvas.no/bilsalget-i-2017/category751.html

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change, 7*, 13. doi:10.1038/nclimate3148

Pérez de Arce, M., & Sauma, E. (2016). Comparison of Incentive Policies for Renewable Energy in an Oligopolistic Market with Price-Responsive Demand. *37*(3), 159-198.

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi:https://doi.org/10.1016/j.rser.2014.02.003

Proença, S., & St. Aubyn, M. (2013). Hybrid modeling to support energy-climate policy: Effects of feed-in tariffs to promote renewable energy in Portugal. *Energy Economics, 38*(0), 176-185. doi:http://dx.doi.org/10.1016/j.eneco.2013.02.013

Rausch, S., & Mowers, M. (2014). Distributional and efficiency impacts of clean and renewable energy standards for electricity. *Resource and Energy Economics, 36*(2), 556-585. doi:10.1016/j.reseneeco.2013.09.001

Rees, W., & Wackernagel, M. (1996). Urban ecological footprints: Why cities cannot be sustainable—And why they are a key to sustainability. *Environmental Impact Assessment Review, 16*(4), 223-248. doi:https://doi.org/10.1016/S0195-9255(96)00022-4

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization, 4*(2), 121-130. doi:10.1177/095624789200400212

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., . . . Foley, J. (2009a). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society, 14*(2), 33.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., . . . Foley, J. A. (2009b). A safe operating space for humanity. *Nature, 461*(7263), 472-475. doi:10.1038/461472a

Rodrigues, R. D. B. (2017). *Hybrid Modeling for Electricity Policy Assessments.* (PhD), Universidad Pondificia Comillas de Madrid, Madrid. Retrieved from https://repositorio.comillas.edu/xmlui/bitstream/handle/11531/18497/TD00246.pdf?sequence=1

Santoyo-Castelazo, E., & Azapagic, A. (2014). Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production, 80*(Supplement C), 119-138. doi:https://doi.org/10.1016/j.jclepro.2014.05.061

Schinko, T., Bachner, G., Schleicher, S. P., & Steininger, K. W. (2017). Modeling for insights not numbers: The long-term low-carbon transformation. *Atmósfera, 30*(2), 137-161. doi:10.20937/ATM.2017.30.02.05

Shoven, J. B., & Whalley, J. (1992). *Applying general equilibrium* (M. Perlman Ed.). Cambridge: Cambridge University Press.

Smith, A. (1776). *An Inquiry into the Nature and Causes of the Wealth of Nations* (E. Cannan Ed.). London: Methuen & Co.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., . . . Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223).

Sue Wing, I. (2006). The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO2 emissions. *Energy Policy, 34*(18), 3847-3869. doi:10.1016/j.enpol.2005.08.027

Timmerman, J., Vandevelde, L., & Van Eetvelde, G. (2014). Towards low carbon business park energy systems: Classification of techno-economic energy models. *Energy, 75*(Supplement C), 68-80. doi:https://doi.org/10.1016/j.energy.2014.05.092

Tokarska, K. B., Gillett, N. P., Weaver, A. J., Arora, V. K., & Eby, M. (2016). The climate response to five trillion tonnes of carbon. *Nature Climate Change, 6*, 851. doi:10.1038/nclimate3036

Trutnevyte, E., Stauffacher, M., Schlegel, M., & Scholz, R. W. (2012). Context-Specific Energy Strategies: Coupling Energy System Visions with Feasible Implementation Scenarios. *Environmental Science & Technology, 46*(17), 9240-9248. doi:10.1021/es301249p

UNFCCC. (2016). *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*. Retrieved from https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

van Beeck, N. M. J. P. (1999). *Classification of Energy Models*. Retrieved from Tilburg: https://pure.uvt.nl/portal/files/532108/777.pdf

van Beeck, N. M. J. P. (2003). *A new decision support method for local energy planning in developing countries.* (PhD), Tilburg University, Tilburg. Retrieved from https://pure.uvt.nl/portal/files/514933/Van_Beeck.pdf

Wall, G., & Gong, M. (2001). On exergy and sustainable development—Part 1: Conditions and concepts. *Exergy, An International Journal, 1*(3), 128-145. doi:https://doi.org/10.1016/S1164-0235(01)00020-6

WCED. (1987). *Our Common Future*. Retrieved from http://www.un-documents.net/our-common-future.pdf

WEC, & Wyman, O. (2017). *World Energy Trilemma Index*. Retrieved from https://www.worldenergy.org/wp-content/uploads/2017/11/Energy-Trilemma-Index-2017-Report.pdf

Wene, C. O. (1996). Energy-economy analysis: Linking the macroeconomic and systems engineering approaches. *Energy, 21*(9), 809-824. doi:10.1016/0360-5442(96)00017-5

Weyant, J. (2017). Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy, 11*(1), 115-137. doi:10.1093/reep/rew018

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E., . . . Fankhauser, S. (1996). Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results. In J. P. Bruce, H. Lee, & E. F. Haites (Eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change* (pp. 367-439). Cambridge: Cambridge University Press.

Whalley, J., & Zhang, S. M. (2011). Tax-induced multiple equilibria. *Applied Economics Letters, 18*(13-15), 1469-1477. doi:10.1080/13504851.2010.543065

Whalley, J., & Zhang, S. M. (2014). Parametric persistence of multiple equilibria in an economy directly calibrated to 5 equilibria. *Economic Modelling, 41*, 356-364. doi:10.1016/j.econmod.2014.05.015

Winning, M. (2013). Advance-IAM. Retrieved 2018-05-31 from https://wiki.ucl.ac.uk/display/ADVIAM/Models

Wolfgang, O. (2006). *Modeller for CO2 systemanalyse*. SINTEF Energiforskning AS.

Paper collection

Paper I

Paper I

An Equilibrium Market Power Model for Power Markets and Tradable Green Certificates, including Kirchhoff's Laws and Nash-Cournot Competition

Energy Economics 70 (2018) 270–288

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's Laws and Nash-Cournot competition

Per Ivar Helgesen *, Asgeir Tomasgard

Norwegian University of Science and Technology, Department of Industrial Economics and Technology Management, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 17 August 2016
Accepted 10 January 2018
Available online 11 January 2018

JEL classification:
C61: Optimization Techniques
Programming Models
Dynamic Analysis
D43: Oligopoly
L94: Electric Utilities
Q48: Government Policy

Keywords:
Tradable green certificates
Equilibrium modeling
Market power
Energy policy
Electric power
Electric transmission

ABSTRACT

We investigate the economic impacts of introducing tradable green certificates to promote electricity produced from renewable energy sources. We formulate a mixed complementarity, multi-region, partial equilibrium model, clearing both the electricity and green certificate markets under the assumption of Nash-Cournot market competition. We introduce a mixed complementarity formulation of the tradable green certificate policy scheme. The main contribution of this paper is to combine a public support scheme for electricity production with a power market model in which strategic generators compete and exercise market power in a capacitated transmission network with spatial energy exchange.

Any policy instrument interfering with the free market solution in a partial equilibrium model will reduce social welfare as a result of deadweight losses from the policy. These welfare losses may be substantial. We show that losses from tradable green certificates influence different market actors depending on the market conditions, but existing firms are likely to bear most of these losses.

In markets with Cournot competition, where producers act strategically, green certificates help to increase market competition if new firms are able to enter the market. Existing firms will not be motivated to compete with new generation capacity. The consumer surplus from introducing tradable green certificates under Cournot competition may increase, despite the deadweight losses the policy incurs.

1. Introduction

This paper models the use of tradable green certificates to support deployment of renewable electricity in the power market. During the last decade, many public support schemes have supported renewable electricity as a way forward to fight climate change, in addition to improving security of energy supply, promoting technological development and innovation, and providing opportunities for employment and regional development (EU, 2009; REN21, 2015). The power sector contributes more than any other sector to the reduction in the share of fossil fuels in the global energy mix (IEA, 2014). Global energy demand is rising, and electricity is the fastest-growing final form of energy. Existing support schemes for electricity include feed-in tariffs, feed-in premiums, tradable green certificates and investment subsidies, possibly combined with tenders/auctions in various forms. In this paper we focus on tradable green certificates (also called 'renewable energy certificates' or RECs). Our model also includes imperfect market competition, since many international electricity markets have been liberalized and redesigned during the last three decades and market competition and possible misuse of market power is a relevant issue in these markets (Borenstein and Bushnell, 1999; Borenstein et al., 1995; Bushnell, 2003).

The main contribution of this paper is to combine a public support scheme for electricity production with a power market model in which strategic generators compete and exercise market power in a capacitated transmission network with spatial energy exchange. Policy instruments constitute interference to the market, and will inevitably lead to deadweight losses. Since we address imperfect competition in this paper, we also get partial welfare gains from the instrument due to reduced market power and thus increased competition. We employ a deterministic partial equilibrium model to find the cost of reaching a target quota of renewable electricity production. Our work builds on previous research on Nash-Cournot equilibria in power markets (Hobbs, 2001; Hobbs et al., 2008; Metzler et al., 2003). We develop a mixed complementarity, multi-region, partial equilibrium model, with an underlying alternating current (AC) network represented by a linearized DC

---

* Corresponding author.
E-mail addresses: per.ivar.helgesen@ntnu.no (P.I. Helgesen), asgeir.tomasgard@ntnu.no (A. Tomasgard).

https://doi.org/10.1016/j.eneco.2018.01.013

network approximation (Schweppe et al., 1988). Both the electricity and green certificate markets are cleared under the assumption of Nash-Cournot market competition. The shared constraints from the network imply that a solution to our model constitutes a Generalized Nash Equilibrium. To our knowledge this is the first model that combines an AC approximation of the transmission network with equilibrium modeling of support schemes and in addition allows imperfect competition.

A literature review follows in Section 2. Section 3 describes the tradable green certificate scheme in further detail. Section 4 describes our mathematical model. In Section 5 we illustrate through a small example how this modeling approach can be used to identify welfare distribution effects between producers, consumers and transmission system owner (TSO), in order to find winners and losers of the game. Section 6 concludes. An Appendix A shows detailed numerical results and supplementary figures from the example.

2. Literature review

The following literature review focuses on equilibrium models for power markets, the inclusion of economic policy instruments in power market models and on modeling physical aspects of the network.

2.1. Perfect versus imperfect competition

Although many policies have been implemented to promote competition, there is still evidence of market power in electricity markets (Bushnell et al., 2008; Dahlan and Kirschen, 2012; Mirza and Bergland, 2015; Pérez de Arce and Sauma, 2016). In order to model imperfect competition we must handle different players participating in the market through a game where they take into account other players' actions. The action of one agent influences the payoff of another agent. A Nash equilibrium describes an equilibrium between agents interacting through their payoffs (Nash, 1950).

In some instances a Nash-Cournot model with multiple players optimizing their own payoffs may be expressed as an optimization problem (Facchinei and Pang, 2003).[1] However, our policy problem includes a tax agent who constrains both primal and dual variables together. Consumers pay a tax on their electricity consumptions in order to finance green certificates that subsidize renewable producers. This restriction produces an equilibrium condition which cannot be expressed in an optimization problem. Thus we formulate an equilibrium model instead of an optimization model. The equilibrium formulation also allows introduction of more realistic demand functions, which would prevent us from expressing our equilibrium problem as an optimization problem (Hobbs et al., 2008).

A generalized Nash equilibrium involves agents that interact both at the level of their payoffs, but also through their strategy sets. The action of an agent can influence the payoff of another agent, but it can also change the set of actions that this agent can undertake. In our model it is easy to see that the strategy of a firm is constrained by production from other firms through the bounds on the energy flows in the network (Kirchhoff's laws). This dependence implies that the equilibrium is a Generalized Nash Equilibrium (Wei and Smeers, 1999).

Our approach is to solve an equilibrium problem consisting of each player's KKT conditions together with market clearing conditions, and solve this problem to obtain a generalized Nash equilibrium.

2.2. Economic models for policy instruments

Economic instruments for achieving environmental goals are classically categorized as either price-based or quantity-based, depending on which of these two variables is chosen by a regulator. By fixing one of the variables (for example price), the other (i.e. quantity) is determined by the market. Traditional price-based policy instruments are taxes and subsidies (Pigou, 1920). The most common policy instruments supporting renewable electricity are feed-in tariffs, feed-in premiums and tradable green certificates. In recent years these instruments are increasingly used in various hybrid policies, especially in combination with competitive bidding (tendering) (Couture et al., 2015; Held et al., 2014; REN21, 2015). Complementarity models are very suitable for policy analysis (Gabriel et al., 2013a). The price-driven versus quantity-driven policy instruments correspond to the duality between model constraints with primal variables representing real-world physical properties (quantities) and the accompanying dual variables (representing prices).

Other papers focus on the dynamics of certificate prices and build models for forecasting prices and volumes in the certificate markets. Such models take into account banking, borrowing and penalty options. The certificate price must equal the discounted expected value in the next time-step, and also the penalty price times the probability of a shortage of credits at the compliance date. Wolfgang et al. (2015) describe a methodology where they simulate climatic variables like wind, sun and reservoir inflow affecting electricity generation, and calculate strategies for the certificate inventory by stochastic dynamic programming using the EMPS model. They report case study forecasted certificate prices based on predefined capacities for production and transmission. Coulon et al. (2015) build a stochastic price model where they allow for dynamic endogenous investment in generation dependent on certificate prices. They demonstrate the important role of market design in determining price behaviour, and suggest a function for deciding the penalty of non-compliance with the certificate obligation. Boomsma and Linnerud (2015) use a somewhat related real options approach to compare market and policy risk under different renewable electricity support schemes. They treat the certificate price as stochastic and find that differences in market risk between support schemes are less than commonly believed due to price diversification. Neither of these models considers an underlying transmission network with its corresponding system effects or the effects of imperfect competition. We include in our model both of these perspectives, at the expense of treating the dynamic development of the support scheme from year to year. We may still include seasonal system dynamics by including time-periods in our model.

2.3. Modeling the economics and the physical aspects of the network

Many studies of electricity markets disregard transmission constraints entirely, or use a transhipment network that ignores Kirchhoff's voltage law (Hobbs et al., 2000). Most of these studies do not consider support schemes. As far as the authors are aware, no previous studies of policy schemes for renewable electricity have included the AC characteristics of transmission networks. We give a short overview of the most relevant models and their approach and scope.

Bushnell (2003) presents a mixed complementarity model to analyze competition between multiple firms possessing a mixture of hydroelectric and thermal generation resources. He studies how Cournot competitors may act strategically and increase profit by allocating more flexible hydro production to off-peak periods than they would under perfect competition. However, he does not consider network transmission constraints. Neither does the study by Linares et al. (2008), which includes regulatory support schemes like tradable green certificates. The authors develop an oligopolistic generation-expansion model for the electricity sector simulating regulatory instruments. They formulate a linear complementarity model which allows the optimization problem for each firm considering the power, carbon and green certificate markets to be solved simultaneously, but do not consider a transmission network or zonal electricity prices. Another study that considers the green certificate support scheme in an equilibrium model without considering transmission is provided by Marchenko (2008). The study evaluates how well a green certificate market mechanism is able to optimize the

---

[1] If an equilibrium problem can be expressed as a variational inequality (VI) with symmetric Jacobian, then an equivalent optimization problem could be found.

total economic effect taking into account external costs compared with other policy instruments. Gabriel et al. (2013b) solve Nash-Cournot energy production games while restricting some variables to be discrete in a recent power market study. Their approach allows for more realistic modeling, for example regarding investments or operational start up decisions. The study neither considers transmission networks nor support scheme aspects.

Other approaches include transmission networks, but assume that electricity can be transported as in a transhipment network. Only Kirchhoff's current law is imposed in such models, while the voltage law (also called Kirchhoff's loop rule) that forces power to flow in parallel paths is disregarded. This approach simplifies the mathematical models, but the corresponding analytic results lead to propositions that are misleading. One example of a common but misleading proposition is that power only flows from nodes with lower prices to nodes with higher prices. This and more examples are thoroughly described by Wu et al. (1996).

Böhringer et al. (2007) investigate economic impacts from using feed-in tariffs or tradable green certificates to promote electricity from renewable energy sources within the EU. Producers compete in a Cournot oligopoly with iso-elastic demand. Their model covers transport between neighboring areas. However the model only handles transport costs between adjacent regions, and arbitrage opportunities through transit areas are not recognized. Kirchhoff's voltage law is not imposed, so transmission is modeled as a transhipment network.

Nagl (2013) looks at renewable support schemes under perfect competition, but extends the study with a time dimension spanning four decades and introduces alternative weather years to capture weather uncertainty. He investigates the effect of weather uncertainty on the financial risk of green electricity producers under feed-in tariffs and tradable green certificates. Electricity demand is assumed to be inelastic. The model relies on transport capacities between adjacent regions. Arbitrage opportunities through transit regions are not recognized, and Kirchhoff's voltage law is not imposed.

The electricity market study by Vespucci et al. (2010) does not include support schemes, but represents the market as a non-cooperative game and assumes that generation firms are Cournot players that decide their strategy in order to maximize their profit. The model operates on a network with five zones and four transmission links. It does not contain cycles, so Kirchhoff's voltage law is not relevant. The study assumes linear demand curves, and each producer solves a mathematical program with equilibrium constraints (MPEC) assuming quadratic production costs. The model does not include time periods.

A different electricity market model approach (without the inclusion of a support scheme) is provided by Vespucci et al. (2013). They use a mixed integer linear programming model of a zonal electricity market. They solve a two-stage model where a dominant producer exerts market power on a capacitated transmission network in order to maximize market share while guaranteeing an annual profit. The model includes hourly decision variables within a year. As the previous one, this model also operates on a network with five zones and four transmission links without cycles, so Kirchhoff's voltage law is not relevant.

Pérez de Arce and Sauma (2016) compare four different incentive policies for renewable energy in an oligopolistic market with price-responsive demand. They include a quota system among the incentive policies, and induce penalties to firms who fail to comply with the obligation instead of introducing a certificate market that provide subsidies. Their network consists of two nodes linked by one line, where Kirchhoff's voltage law is not relevant.

In order to calculate more realistic network electricity flows, the linearized "DC" load flow model (Schweppe et al., 1988) is frequently used. This is an approximation of an alternating current (AC) model, focusing on real power with linear approximations of the power flow equations. Losses are often disregarded, but several different DC approximations are discussed by Stott et al. (2009).

Several studies have combined a DC approximated transmission network with oligopolistic market models (Hobbs, 2001; Hobbs et al., 2008; Metzler et al., 2003; Neuhoff et al., 2005). None of these includes policy support schemes for renewable electricity. Hobbs (2001) uses constant power transmission distribution factors (PTDF) to describe the power flow, and shows that a model with bilateral power markets and arbitrage is equivalent to a POOLCO power market in which each producer sells power to the grid at their area price. The transmission model is extended with nonlinear losses, controllable DC lines and phase shifters in Hobbs et al. (2008). The PTDF-based formulation is not possible, since changes in line loadings with respect to changed injections will be nonlinear. Kirchhoff's voltage law is instead imposed by restricting the sum of potential differences (voltages) around any network loop to be zero. A similar version is used by Bjorndal and Jornsten (2007), who study benefits from congestion management using an optimization model that maximize social welfare assuming perfect competition, linear demand functions and affine production cost functions.

A recent modeling advance is given by Munoz et al. (2013), who study transmission investments and their cost and performance implications for renewable portfolio standards assuming that the market equilibrium is the solution that minimizes total system costs. They show that ignoring transmission constraints when considering investments in renewables will increase the total costs. Perez et al. (2016) proceed further to include trading of renewable energy certificates between regions with different renewable obligations and thus regional certificate prices. They find that most of the economic benefits are captured if approximately 25% of renewable energy credits are allowed to be acquired from out of state. They however assume perfect competition, inelastic demand and that renewable targets are met in the most cost-efficient manner.

Limpaitoon et al. (2011) combine an oligopolistic electricity market, a lossless DC-approximated transmission network and a cap-and-trade emissions permits market. They show that market structure and congestion can have significant impact on the market performance. Limpaitoon et al. (2014) proceed further to analyze market combinations in the permits market, and how initial levels of permit allocations influence the results. They show that a firm with more efficient technologies and high levels of initial permits can withhold permits, and that strategic permit trading may influence patterns of transmission congestion. Their model covers a cap-and-trade permits market instead of a green certificate market. The cap-and-trade scheme limits greenhouse gas emissions by creating a cost on emissions, instead of rewarding new renewable generation technologies which do not emit greenhouse gases. The permits lead to welfare redistribution between firms whereas the cost of certificates are transferred to consumers via a tax, thus creating different welfare redistribution outcomes. Their model does not consider arbitragers, who eliminate any non-cost based price differences between regions.

Our model combines inclusion of transmission constraints and investments in renewables, as recommended by Munoz et al. (2013). We develop one integrated complementarity model capable of representing regional power markets with imperfect competition among multiple players, system effects from a physical AC network affecting multiple regional markets and a tradable green certificate policy instrument to support renewable electricity. We also include arbitragers that are able to exploit non-technical price differences between regions. To our awareness no model combining these elements exists in the previous literature, and our results show that all of these aspects are of importance when studying the effects of a policy scheme.

3. The tradable green certificate scheme

The tradable green certificate system is a market based support scheme providing financial support to promote new electricity generation based on renewable energy sources. For each megawatt-hour

(MWh) of renewable energy produced, a tradable certificate is issued to the generator, who can then sell the certificate in the marketplace. The demand could be voluntary (based on preferences), or mandatory as a quota obligation on retailers or end-users (Nilsson and Sundqvist, 2007). It is common to design the system as technology neutral in order to promote competition between technologies eligible for certificates, for example by recognizing that all renewable energy sources in accordance with directive EU Directive 2009/28/EC (EU, 2009) qualifies for the right to certificates. The system can also be geared towards particular types of renewable energy (Coulon et al., 2015; El Kasmioui et al., 2015).

The authorities must ensure the following actions in a typical application:

- decide a mandatory quota obligation which is imposed on market participants
- issue certificates to producers of eligible electricity generation
- maintain a registry over certificates, keeping track of traded certificates
- cancel redeemed certificates according to the quota obligation
- impose penalties to parties who do not fulfill their quota obligation

Fig. 1 shows demand and supply of green certificates based on Morthorst (2000), who describes development of a green certificate market. The demand for electricity certificates is inflexible, and represented by a vertical demand curve. The supply curve is a mixture of short-run marginal cost (SRMC) for existing renewable generation and long-run marginal cost (LRMC) of new renewable generation. The figure shows a situation where the electricity price plus certificate price must cover the LRMC of new renewable generation. The certificate price will correspond to the needed markup to the electricity price such that the last renewable capacity can recover its capital costs (included in LRMC).

Fig. 2 shows a theoretical market solution, indicating how the certificate price adds on the electricity price such that the last produced unit covers its (long run) marginal cost.

The price p_0 is the equilibrium market price before the green certificate scheme is introduced. With introduction of certificates we see renewable electricity generation crowding out parts of the old generation. The electricity price then decreases to p_p, thus remaining old producers receives p_p-p_0 less than before for each sold unit. Renewable generation earns the producer price of electricity plus the green certificate price ($p_p + p_{gc}$). Consumers pay the consumer price p_c, which is equal to the producer price of electricity plus the tax rate that is necessary to finance the value of the green certificates (indicated by the blue rectangle). Thus the tax rectangle and the certificate rectangle should cover the same area.

It is evident that ceteris paribus, the market solution in Fig. 2 would imply a significant transfer from old producers (decreasing their profit) to consumers (increasing their consumer surplus), while new producers earn a profit from the combined electricity and certificate income.

Introducing a financial support scheme to remunerate expensive renewable power generation instead of cheaper (polluting) power generation implies that a welfare loss is imposed to society, unless the climate benefits of the scheme are quantified. Market regulations are justified when they can alleviate market imperfections such as externalities, which prevent the market from optimal resource allocation and maximized welfare. Burning fossil fuels that emit greenhouse gases today may for example have big future societal costs that are not reflected in today's prices and not taken into account by market participants.

Our partial equilibrium model does not capture the benefits of the policy scheme, so introducing a support scheme will inevitably result in a welfare loss. These losses are attributed to the policy instruments and are called deadweight losses. Fig. 2 indicates a deadweight loss from the green certificates, and an additional deadweight loss from the tax. In our analyses we investigate who bears these welfare losses. Regardless of this, we assume that the overall targets for the green certificate support scheme justify the welfare losses we find, but that is not within the scope of the model.

4. Mathematical model

We have *r* regions and *f* firms. There are *i* generation technologies available, and some of these are eligible for green certificates which are traded in a common market across the regions. A levelized production cost is associated with each technology. Each firm can be located in several regions, and operate several technologies. Regions are connected by links with limited capacity. If there are price differences between regions, the transmission system operator (TSO) earns the difference on the power flowing through the link. A transport cost could also be associated with each link as a fixed rate, generating additional income to the grid owner (TSO). For simplicity, we assume no such fixed rates in the model presented here.

We assume that electricity supply is characterized by the existing technologies' SRMC, and by the LRMC for technologies that require capacity investments. Renewable electricity generation receives tradable green certificates according to production volume. We assume that the certificate price is formed such that the combined income from electricity and green certificates covers the LRMC for the last capacity investment that fulfills the quota obligation. In the following we just refer to marginal costs of production.

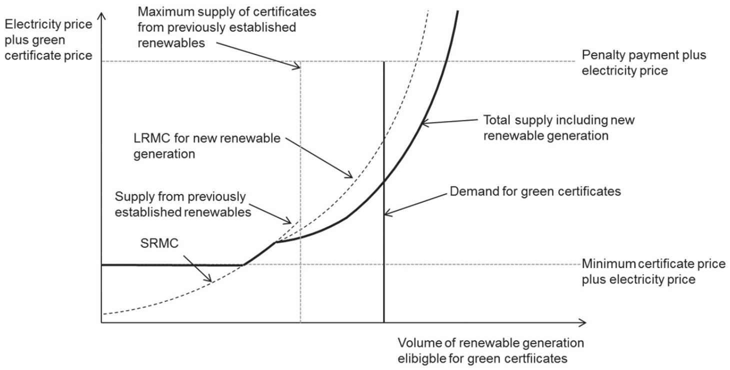

Fig. 1. Demand and supply at a green certificate market.

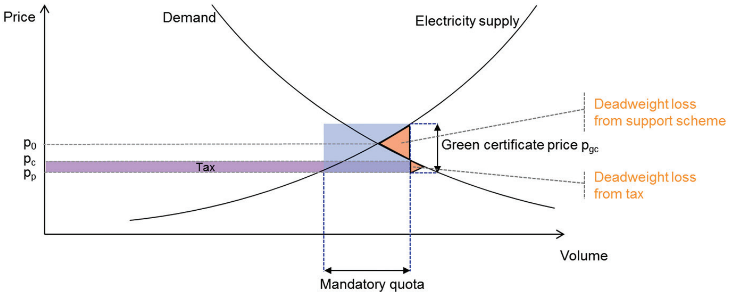

Fig. 2. Market solution in a tax financed certificate support scheme.

Furthermore we assume that electricity suppliers choose to comply with the quota requirement, instead of paying a quota obligation penalty fee. Our model is static in the sense that we consider a yearly quota and a certificate market in equilibrium. We do not consider banking or lending certificates. Although we consider a representative year, we could decompose this chosen period into time segments as in standard capacity expansion models. We do not include such a time segment dimension here in order to simplify notation, but in empirical applications it would be essential to recognize the diverse operation of the system in different time segments.

Furthermore we assume that the electricity and certificate markets are complete, such that there is a unique price for shared resources - and all relevant players share this price. In an incomplete market, players may price the shared constraints differently.

Let us define the following notation.

Sets

R	regions (we assume that each node represents a region), indexed by r and k
I	generation technologies, indexed by i
I_c	generation technologies eligible for electricity certificates, indexed by i
F	electricity producing firms, indexed by f or g
N	loops in electricity network, indexed by ν
K	lines in electricity network, indexed by (r, k)
K_ν	lines in loop ν, indexed by (r, k)

Parameters

c_i	marginal cost of production for technology i
$Q_{0,\,r}$	demand quantity intercept in region r
$P_{0,\,r}$	price intercept in region r
L_{rk}	transport capacity from region r to region k
R_{rk}	reactance on link from region r to region k
G_{ifr}	production capacity of technology i in firm f in region r
$k_{rk\nu}$	indicates if line from region r to region k is included in loopflow ν, takes values -1, 0 or 1
V	green certificate volume

Variables

s_{fr}	supply by firm f to region r
x_{ifr}	production in firm f using technology i
z_{rk}	net flow from region r to region k
a_r	arbitrage flow into region r
p_r	supplier price of electricity in region r
w_r	(dual) transport cost from the grid into region r
κ_ν	(dual) grid transport cost to impose Kirchhoff's voltage law in loop ν
τ_{rk}	(dual) price on grid transmission capacity from region r to region k
φ_{ifr}	(dual) price on production capacity by firm f and technology i
ω_f	(dual) marginal income by firm f
γ	(dual) marginal cost of restricting net arbitrage to zero
μ	price of green certificate
t_μ	consumption tax rate to finance the green certificate support scheme

4.1. Producer problem (Cournot competition)

The producers choose their generation and sales in order to maximize profit. They are aware that their production will influence the market price (Cournot competition). Producer f solves the following quadratic program:

$$\underset{s_{fr},x_{ifr}}{Max} \sum_{r\in R} \left[(p_r - w_r)s_{fr} - \sum\nolimits_{i\in I}(c_i - w_r)x_{ifr} + \sum\nolimits_{i\in I_c}\mu\, x_{ifr}\right]$$

$$= \sum\nolimits_{r\in R}\left[\begin{array}{c}\left(P_{0r} - \left(\dfrac{P_{0r}}{Q_{0r}}\right)\left(\sum\nolimits_{g\in F} s_{gr} + a_r\right) - t_\mu - w_r\right)s_{fr} \\ -\sum\nolimits_{i\in I}(c_i - w_r)x_{ifr} \;+\; \sum\nolimits_{i\in I_c}\mu\, x_{ifr}\end{array}\right]$$

Each producer maximizes its profit, which is comprised by three components: income, production cost and certificate income. The wheeling cost w_r is paid to the TSO for transporting power s_{fr} to region r from the transmission network. When the producer generates power x_{ifr} in region r, the TSO pays the regional wheeling fee to the producer for receiving power into the network. The producer also receives the certificate price μ for each MWh of renewable electricity x_{ifr} generated using a technology eligible for certificates $i \in I_c$.

$$Supply: \sum\nolimits_{r\in R} s_{fr} - \sum\nolimits_{i\in I}\sum\nolimits_{r\in R} x_{ifr} \le 0, \quad f\in F \quad (\omega_f)$$

The supply constraint inhibits the producer from selling more power s_{fr} than it produces x_{ifr}. It is possible to produce more power than supplied. This would imply that the marginal income ω_f is zero.

$$Prodlim: \quad x_{ifr} \le G_{ifr}, i\in I, f\in F, \quad r\in R \quad \left(\varphi_{ifr}\right)$$

The prodlim constraint represents production limits. We assume that each production facility has an upper capacity bound G_{ifr}, with a shadow price of φ_{ifr}. At last we add nonnegativity constraints on the decision variables for supply and generation.

$$s_{fr} \ge 0, x_{ifr} \ge 0$$

The Karush-Kuhn-Tucker (KKT) conditions are found by formulating the Lagrangian function and taking partial derivatives with respect to the independent variables and to the Lagrange-multipliers (dual variables). We collect the complete set of KKT conditions in the end of this section.

4.2. Grid owner/TSO problem (Nash-Bertrand assumption)

We assume that the grid owner naively acts as a price taker, and chooses grid flows to maximize its profit while adhering to Kirchhoff's current and voltage laws and transmission capacities.

$$\underset{z_{rk},z_{kr}}{Max}\sum_{r\in R}\left[w_r\left(\sum_{f\in F}s_{fr}-\sum_{f\in F}\sum_{i\in I}x_{ifr}+a_r\right)\right]$$

The grid owner maximizes his income from the wheeling fee on power flowing to each region.

$$KCL:\sum_{f\in F}s_{fr}-\sum_{f\in F}\sum_{i\in I}x_{ifr}+a_r-\sum_{k\in R}z_{kr}+\sum_{k\in R}z_{rk}=0, r\in R\quad(w_r)$$

The KCL constraint states Kirchhoff's current law: The sum of currents flowing into a node or region is equal to the sum of currents flowing out of that node, so the sum of all currents meeting in region r must be zero.

$$KVL:\sum_{(r,k)\in K_v}R_{rk}(z_{kr}-z_{rk})=0,\quad v\in N\quad(\kappa_v)$$

Kirchhoff's voltage law (also called Kirchhoff's loop rule) is represented by the KVL constraint. The law says that the directed sum of the electrical potential differences (voltages) around any closed cycle in the network is zero. A potential difference over the cycle would create a current, and we cannot have a positive flow running through any cycle in the network. The sum of flows adjusted by the reactance R_{rk} of the line between region r and region k must be zero.

$$Flowlim: z_{rk}\le L_{rk},\qquad (r,k)\in K\qquad(\tau_{rk})$$

The flowlim constraint represents the capacity of the lines. This capacity depends on temperature, security limits and other parameters, but we assume a directed net transfer capacity L_{rk} for each line.

We also need nonnegativity constraints on the directed flow variables.

$$z_{rk}\ge 0$$

4.3. Arbitrager (Nash-Bertrand assumption)

If there are price differences between regions, arbitragers try to buy power at a lower price and sell at a higher price, exploiting these price differences.

We assume that the arbitrager is a price taker, and solve the following profit maximization problem:

$$\underset{a_r}{Max}\sum_{r\in R}[(p_r-w_r)a_r]$$

The arbitrager will buy power in region k and sell to region r if $p_r - w_r > p_k - w_k$.

$$Arbizero:\sum_{r\in R}a_r=0\quad(\gamma)$$

Since the arbitrager does not generate power, the sum of regional arbitrage quantities a_r must be zero. These variables can be both positive and negative.

$$a_r\text{ free},\qquad r\in R$$

4.4. Tax agent

The tax agent minimizes the tax needed to finance the green certificates that are necessary to fulfill the renewable quota obligation.

$$\underset{t_\mu}{\text{Min}}\, t_\mu$$

The tax rate should be as low as possible, in order to minimize the socioeconomic deadweight loss the tax will incur. The tax on electricity must cover the value of the certificates.

$$Tax:\sum_{r\in R}\sum_{f\in F}s_{fr}t_\mu\ge\sum_{r\in R}\sum_{f\in F}\sum_{i\in I_c}x_{ifr}\mu\quad(\lambda_1)$$

The tax rate is nonnegative.

$$t_\mu\ge 0\quad(\lambda_2)$$

4.4.1. KKT conditions

$$\frac{\partial\mathcal{L}}{\partial t_\mu}=1-\lambda_1\left(\sum_{r\in R}\sum_{f\in F}s_{fr}\right)-\lambda_2=0$$

$$\frac{\partial\mathcal{L}}{\partial\lambda_1}=-\sum_{r\in R}\sum_{f\in F}s_{fr}t_\mu+\sum_{r\in R}\sum_{f\in F}\sum_{i\in I_c}x_{ifr}\mu\le 0\quad\perp(\lambda_1\ge 0)$$

$$\frac{\partial\mathcal{L}}{\partial\lambda_2}=-t_\mu\le 0\quad\perp(\lambda_2\ge 0)$$

We see from $\frac{\partial\mathcal{L}}{\partial t_\mu}$ that at least one of the dual variables must be strictly positive.

$$\lambda_1>0\Rightarrow\sum_{r\in R}\sum_{f\in F}s_{fr}t_\mu-\sum_{r\in R}\sum_{f\in F}\sum_{i\in I_c}x_{ifr}\mu=0$$

$$\lambda_2>0\Rightarrow t=0$$

Thus the tax financing condition can be written:

$$\left(0\le\sum_{r\in R}\sum_{f\in F}s_{fr}t_\mu-\sum_{r\in R}\sum_{f\in F}\sum_{i\in I_c}x_{ifr}\mu\right)\perp(t_\mu\ge 0)$$

4.5. Consumer/market clearing

The representative consumer acts as a price taker. We assume a linear demand curve. Her willingness to pay for a quantity q_r is $w_r(q_r)=P_{0r}-\frac{Q_{0r}}{P_{0r}}q_r$. The consumer wants to maximize her consumer surplus:

$$\underset{Q_r^*}{Max}\int_0^{Q_r^*}(w_r(q_r)-p_r-t_\mu)\,dq_r\qquad\text{where}\quad w_r(q_r)=P_{0r}-\frac{Q_{0r}}{P_{0r}}q_r$$

4.5.1. KKT condition

$$\frac{d}{dQ_r^*}\left[\int_0^{Q_r^*}w_r(q_r)\,dq_r-p_rQ_r^*-t_\mu Q_r^*\right]=0$$

$$P_{0r}-\frac{P_{0r}}{Q_{0r}}q_r=p_r+t_\mu\ \text{ where }\ q_r=\sum_{f\in F}s_{fr}+a_r$$

Thus the market clearing condition which maximizes consumer surplus is:

$$P_{0r} - \frac{P_{0r}}{Q_{0r}}\left(\sum_{f \in F} s_{fr} + a_r\right) - \ p_r - t_\mu = 0, p_r \text{ free}, r \in R$$

4.6. Certificate/quota constraint

Regulating authorities decide a volume V of new renewable electricity production.

$$Elcert: \sum_{i \in I_c}\sum_{f \in F}\sum_{r \in R} x_{ifr} \geq V \qquad \perp (\mu \geq 0)$$

The dual price μ of this constraint becomes the value of certificates. This is the lowest certificate value needed to achieve the target of renewable production. Producers could choose to generate more than the target, in which case the certificate value will be zero.

The combined KKT conditions and the additional quota constraint that constitute the full equilibrium model are as follows:

Producers:

$$\left(0 \leq -p_r \ + \frac{P_{0r}}{Q_{0r}} s_{fr} + w_r + \omega_f\right) \perp (s_{fr} \geq 0), f \in F, r \in R$$

$$\left(0 \leq c_i - w_r - \mu + \varphi_{ifr} - \omega_f\right) \perp (x_{ifr} \geq 0), f \in F, r \in R, i \in I_c$$

$$\left(0 \leq c_i - w_r \qquad + \varphi_{ifr} - \omega_f\right) \perp (x_{ifr} \geq 0), f \in F, r \in R, i \in I \backslash I_c$$

$$\left(0 \leq \sum_{i \in I}\sum_{r \in R} x_{ifr} - \sum_{r \in R} s_{fr}\right) \perp (\omega_f \geq 0), \ \ f \in F$$

$$(0 \leq G_{ifr} - x_{ifr}) \perp \left(\varphi_{ifr} \geq 0\right), i \in I, f \in F, r \in R$$

TSO:

$$\left(0 \leq w_r - w_k + \sum_{v \in N} k_{rkv}\kappa_v + \tau_{rk}\right) \perp (z_{rk} \geq 0), (r,k) \in K$$

$$\left(\sum_{f \in F} s_{fr} - \sum_{f \in F}\sum_{i \in I} x_{ifr} + a_r - \sum_{k \in R} z_{kr} + \sum_{k \in R} z_{rk} = 0\right) \ (w_r \text{ free}), r \in R$$

$$\left(\sum_{(r,k) \in K_v} R_{rk}(z_{kr} - z_{rk}) = 0\right) \ (\kappa_v \text{ free}), v \in N$$

$$(0 \leq L_{rk} - z_{rk}) \perp (\tau_{rk} \geq 0), \ \ (r,k) \in K$$

Arbitrager:

$$(-p_r + w_r + \gamma = 0) \ (a_r \text{ free}), r \in R$$

$$\left(\sum_{r \in R} a_r = 0\right) \ (\gamma \text{ free})$$

Tax agent:

$$\left(0 \leq \sum_{r \in R}\sum_{f \in F} s_{fr} t_\mu - \sum_{r \in R}\sum_{f \in F}\sum_{i \in I_c} x_{ifr}\mu\right) \perp (t_\mu \geq 0)$$

Certificate/quota condition:

$$\left(0 \leq \sum_{i \in I_c}\sum_{f \in F}\sum_{r \in R} x_{ifr} - V\right) \perp (\mu \geq 0)$$

Market clearing condition:

$$\left(P_{0r} - \frac{P_{0r}}{Q_{0r}}\left(\sum_{f \in F} s_{fr} + a_r\right) - \ p_r - t_\mu = 0\right) \ (p_r \text{ free}), r \in R$$

5. Illustrative example

In our example, authorities want to subsidize electricity generated by renewable technologies at the expense of cheaper but polluting technologies using fossil fuels. The example is based on and expanded from Hobbs (2001). It illustrates the application of the suggested model, and is designed to permit verification by the reader. We have three price zones, $r = 1, 2, 3$ and each pair of zones is interconnected by a single transmission line (see Fig. 3). All three lines have equal impedances. Each zone has customers, and the demand functions are

$$w_r(q_r) = 40 - \frac{40}{500} q_r, \text{for } r = 1, 2 \text{ and } w_3(q_3) = 32 - \frac{32}{620.4} q_3.$$

There are two producers $f = 1, 2$, each with one generator. Firm 1's generator is sited at $r = 1$, while 2's is at $r = 2$. Both generators have unlimited capacity, and a constant marginal cost: \$15/MWh for firm 1, and \$20/MWh for firm 2. The only transmission cost arises from congestion.

We consider two different transmission systems. One with infinite transmission capacity and no congestion, and one with congestion on a capacitated transmission line between region 1 and 2. The flow capacity is 25 MW either direction. These two cases are solved for three types of competition: Perfect competition, Cournot competition without arbitrage and Cournot competition with arbitrage. The arbitrager eliminates price differences between regions, erasing any non-cost based differences in price. Such price differences do not appear under perfect competition.

We expand the example by introducing a quota obligation of 80 MWh renewable electricity. This represents a production increase between 8 and 15% compared to previous production in the different cases. We assume that all existing generation is based on fossil fuels, and that both existing firms may invest in renewable generators with a LRMC equal to \$24/MWh (located in the same region as the existing generator). We also introduce potential new firms in regions 1 and 2 with the opportunity to invest in the same generation technology with the same costs as the existing firms. A regulator issues a certificate for each MWh of renewable electricity, and electricity suppliers must buy its relative share of certificates. The certificate cost is allocated to consumers by a certificate tax on top of the electricity price.

Introducing new firms under Cournot competition has its own effects regardless of the support scheme. We want to separate these effects from the support scheme effects, so we define three variants for each case (in addition to the original case). The variants are summarized in Table 1.

The model has been programmed in GAMS,[2] and the mixed complementarity problem has been solved with the PATH solver (Dirkse and Ferris, 1995).

Numerical results from each case variant are reported in the Appendix A, see Tables 3 to 5. The tradable green certificates together with the consumer tax lead to large deadweight losses in our numerical example, amounting to >100% of the total certificate value in all cases.

---

[2] General Algebraic Modeling System, see www.gams.com.

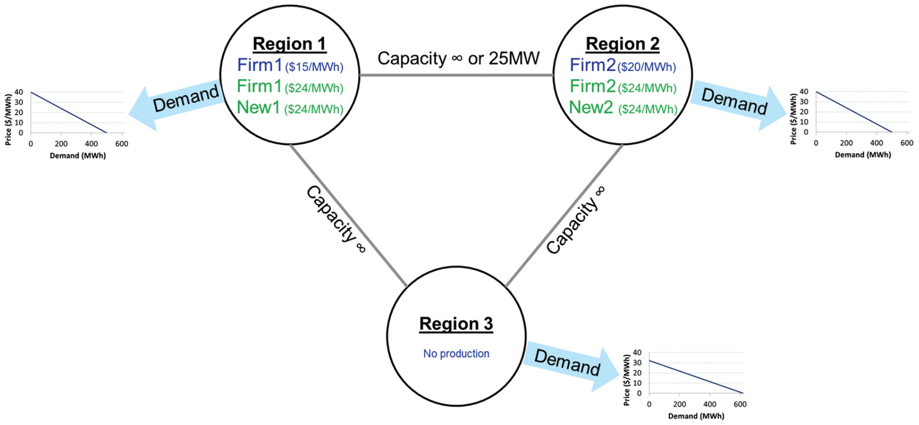

Fig. 3. Illustrative example.

The reason for this extreme result is that the certificates cover the increase in production costs, but provide no profit to producers because of constant marginal cost. Consumers pay for more expensive production, without getting any extra direct benefit (keep in mind that the reason for the scheme is not represented in the partial model, so these benefits are not captured). Thus the whole value of the certificates is lost, and the deadweight loss from the consumer tax results in a net loss.

Our analysis proceeds as follows: First we describe properties of each case equilibrium briefly, and then discuss a sensitivity analysis in one of the cases to get a sense of the equilibrium. Then we look at welfare effects of the different case variants, and summarize the aggregated social welfare effects for consumers and firms.

5.1. Perfect competition - uncapacitated network

In this case it does not matter where new production enters, since there is no lack of network capacity. The cheapest generation (wherever located) will enter the market. Since all renewable generators have identical cost, the model solution is indeterminate - any distribution of the mandatory quantity between the four firms is a valid solution. (In Table 5 the 80MWh is arbitrarily allocated to the existing firm $f = 2$.)

The certificate price must cover the difference between current marginal generation marginal renewable generation (equal to 24 minus 15). Producers get no profit from the new generation, since electricity price plus certificate price only cover production cost. Since we have only one renewable technology, the total certificate value balances the cost of certificate production and the scheme does not contribute to increased welfare at all. Then the tax has a negative welfare effect. The new and more expensive generation replaces some of the old and cheaper (but presumably dirtier) generation, and consumers face a higher total price when we include the certificate tax. The total certificate value is 720, but the deadweight loss of the certificates and the tax is higher: 733. The scheme decreases net social welfare more than the scheme costs. The welfare loss depends on the cost of renewable electricity - the higher the cost, the higher the deadweight loss.

5.2. Perfect competition - $LinkCapacity_{12} = 25$ MW

The capacitated network favors production in Region 2, since there is a network bottleneck towards the cheapest generation in Region 1. All renewable generation will be located in Region 2 under perfect competition. As long as the existing and the new firm in region 2 have the same marginal cost of renewable generation, it does not matter which of these firms is producing.

Region 2 has a higher electricity price, since the fossil generation in this region is more expensive than in Region 1. The certificate price needed to cover the marginal renewable generation cost will be correspondingly *lower* (equal to 24 minus 20) compared with the uncapacitated case. Producers earn zero profit, but the TSO earns a profit which does not change when the tradable certificate scheme is introduced. Consumers must pay a certificate tax, which expose them to increased electricity prices. Thus consumer surplus decreases in this case.

5.3. Cournot competition, no arbitrage - uncapacitated network

Under Cournot competition, both new firms will enter the market and generate equal amounts of renewable electricity (since they have identical costs). There is no lack of network capacity, thus the *location* of new firms does not matter. New firms will make positive profits, at the expense of existing firms. Consumer electricity prices after tax decrease, thanks to increased production – thus the consumer surplus increases. Since the electricity prices are high under Cournot competition, the resulting certificate price becomes lower than under perfect competition.

5.4. Cournot competition, no arbitrage - $LinkCapacity_{12} = 25$ MW

New firms still enter the market, but now the location matters. The capacitated network favors production in Region 2, but the new firm in region 1 also enters the market, generating 14 out of 80 MWh. This

Table 1
Case variants.

Variant	Firms able to invest in renewable generation	Support scheme	Comment
0)	Only existing firms	No mandatory quota	Original example
a)	Only existing firms	Mandatory quota with green certificates	Isolated support scheme effects without new firms
b)	New firms may enter	No mandatory quota	Isolated effects from introducing new firms
c)	New firms may enter	Mandatory quota with green certificates	Combined effects from new firms and support scheme

case has the highest regional electricity price, and correspondingly the lowest certificate price.

5.5. Cournot competition with arbitrage - uncapacitated network

Price differences are arbitraged away in this case, so the electricity price is equal in all regions – and lower than the marginal cost of renewable generation. This means that new firms will not enter the market without a mandatory quota with corresponding support. The certificate price and certificate tax remain the same in the arbitrage case as in the one without arbitrage. Both new firms enter and the location of the new firms does not matter. Since they have the same marginal production cost, they generate the same amounts of electricity. Consumers face a lower after tax electricity price than before the scheme, so consumer surplus increases.

5.6. Cournot competition with arbitrage - $LinkCapacity_{12} = 25$ MW

The capacitated network again favors the new firm in region 2, and when arbitrage is possible conditions are even harder for the new firm in region 1. It is able to run with a small profit, and produces 8 out of 80 MWh. The new firm in Region 2 generates the remaining 72 MWh. Electricity price in Region 2 before the support scheme is above the renewable marginal cost of production, so the new firm in Region 2 would enter the market even without a mandatory quota and corresponding support (but with a smaller production volume of 29 MWh).

Generation from each technology in each case is depicted in Fig. 8 in the Appendix A. In cases with Cournot competition there may be opportunities for new firms to enter the market and be able to earn a profit even without a mandatory renewable quota. When arbitrage is possible, competition is harder and new firms produce less compared to cases without arbitrage.

Regional production depends strongly on network transmission capacities. New firms produce equally when the network is uncapacitated. The capacitated network favors production in Region 2, but we see that the new firm in Region 1 still generates a small share of the renewable electricity in the capacitated Cournot cases with mandatory renewable generation quota.

5.7. Sensitivity analysis

Under Cournot competition new firms have higher incentives to employ new technology than existing firms. With equal marginal costs of production, profit gains are higher for new firms than existing ones. In this sensitivity analysis we investigate what happens if the existing Firm 2 has a superior renewable technology, allowing to generate renewable electricity with lower production cost than new firms. We assume a limited capacity of 100 MWh, due to limited natural resources.

We find that marginal production cost must be considerably lower for the existing firm to produce at the expense of new firms that want to enter the market. This is evident in Fig. 4, which shows electricity production by firm in the case of Cournot competition without arbitrage in a capacitated network. Remember that new firms (New 1 and New 2) have a renewable cost of $24/MWh.

If old Firm 2 can generate renewable electricity at a lower cost than the original technology ($20/MWh), it runs at full capacity. The certificate price is zero, since the renewable quota target is surpassed. The electricity price in region 2 is still high enough to allow the new firm “New2” to enter the market. Corresponding electricity prices and certificate prices are reported in Fig. 5. If the renewable generation cost of Firm 2 increases above $20, the firm cuts its renewable generation and the certificate price must cover the difference between the renewable and the fossil generation cost. All regional prices decrease with increasing generation cost of Firm 2, but the certificate price increases more. At a generation cost of $20.4/MWh firm “New1” is able to enter the market, since electricity price in Region 1 plus certificate price has risen above the production cost of $24/MWh. If Firm 2’s renewable generation cost is above $21.45/MWh, the certificate price does no longer cover the price difference and Firm 2 chooses not to compete with new firms on renewables, despite having a lower production cost.

In this particular case the consumers gain (see Fig. 5) when new firms conquer market shares. Thanks to increased market competition they pay lower electricity prices even though they must finance the green certificates that support more expensive renewable generation. Thus the consumer surplus increases, despite the deadweight losses from the support scheme. Similar sensitivity analyses for each Cournot case are reported in the Appendix A.

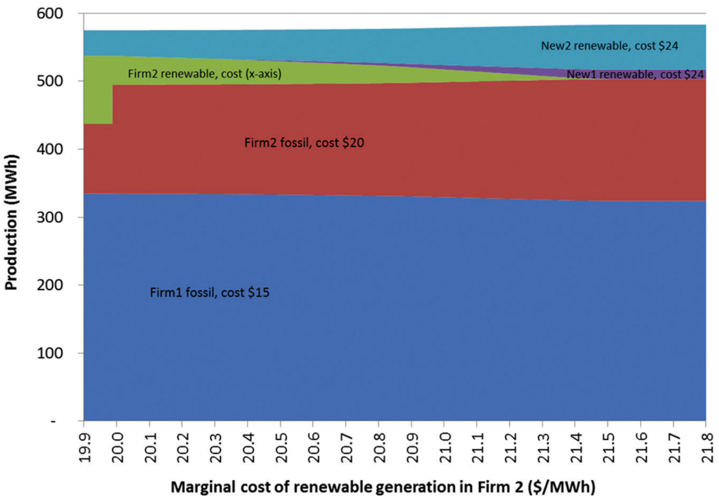

Fig. 4. Equilibrium under Cournot competition without arbitrage in capacitated network.

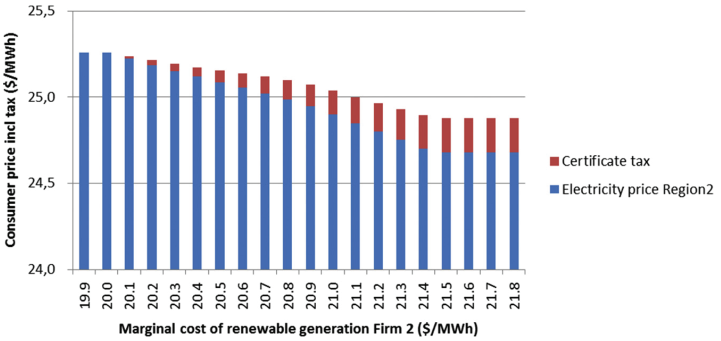

Fig. 5. Consumer price in region 2.

5.8. Social welfare effects in different cases

The sensitivity analysis of our selected case indicated that consumer surplus may increase. Fig. 6 shows the aggregated social welfare effects for consumers (measured by consumer surplus) and firms (measured by profit) for each of our six cases (looking at variant c) where new players may enter the market). All cases show reductions in net social welfare.

Perfect competition constitutes the strongest form of competition among suppliers, and firms earn no profit in our example (but the TSO earns a profit in the capacitated cases). Consequentially consumers must pay the full deadweight loss incurred by the certificate scheme.

In contrast, under Cournot assumption the competition among firms is weaker, and firms make high profits. The certificate scheme leads to increased consumer surplus under Cournot competition while total firm profit decrease thanks to increased competition among suppliers. New firms enter the market and increase the market competition since they increase their profits from renewable generation more than the existing Cournot players do. The existing firms choose not to generate renewable electricity, in order to hold back production and keep prices as high as possible. These results confirm our qualitative analysis in Section 3.

None of the cases provides increased profits to the producers (in total). New firms may still make positive profits, but these come at the expense of existing firms. As market competition gets more intense, firms lose profit and consumers gain surplus (regardless of the support scheme).

In order to assess deadweight losses from the support scheme, we need to decompose the social welfare changes into separate effects:

1) Both the tradable certificate scheme with mandatory renewable quota and the accompanying consumer tax have deadweight losses.
2) New producers entering the market will increase competition regardless of the green certificates, leading to welfare changes that are independent of the support scheme.

In Fig. 7 we have decomposed the net social welfare changes for each of the cases. The first column shows the original net social welfare. Column number two and three shows the change in consumer surplus and firms profit respectively, from allowing new firms to enter the market. Column 4 and 5 shows the combined scheme and tax deadweight losses for consumers and firms respectively, leading to the new net social welfare shown in column 6.

Allowing new firms under Cournot competition has its own welfare effects, which are negative for (existing) firms and positive for consumers. Notice that arbitrage makes it unprofitable for new firms to enter the market in the uncapacitated network Cournot case without the mandatory renewable quota.

Fig. 7 shows that welfare effects are diverse, even in this small example. Perfect competition provides the highest net social welfare, but also the highest deadweight loss from the certificate scheme, which in these cases hits the consumers. In the Cournot cases the deadweight losses hit the old firms, for which the entire losses are even higher than the

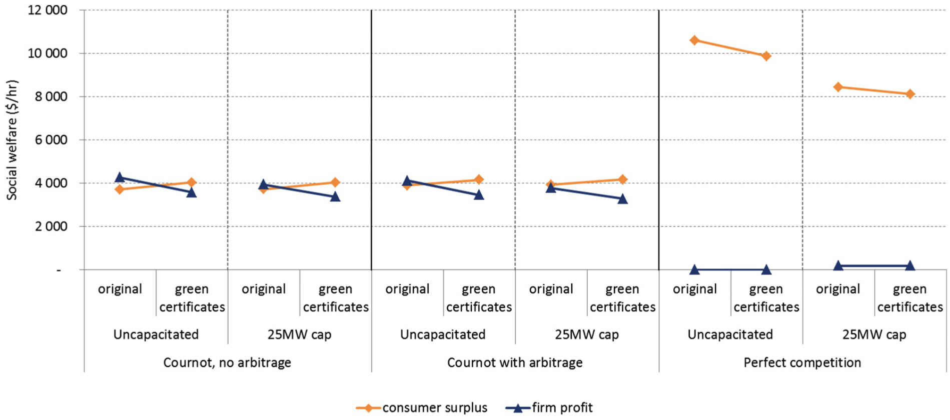

Fig. 6. Social welfare effects for consumers and firms by case with increasing market competition.

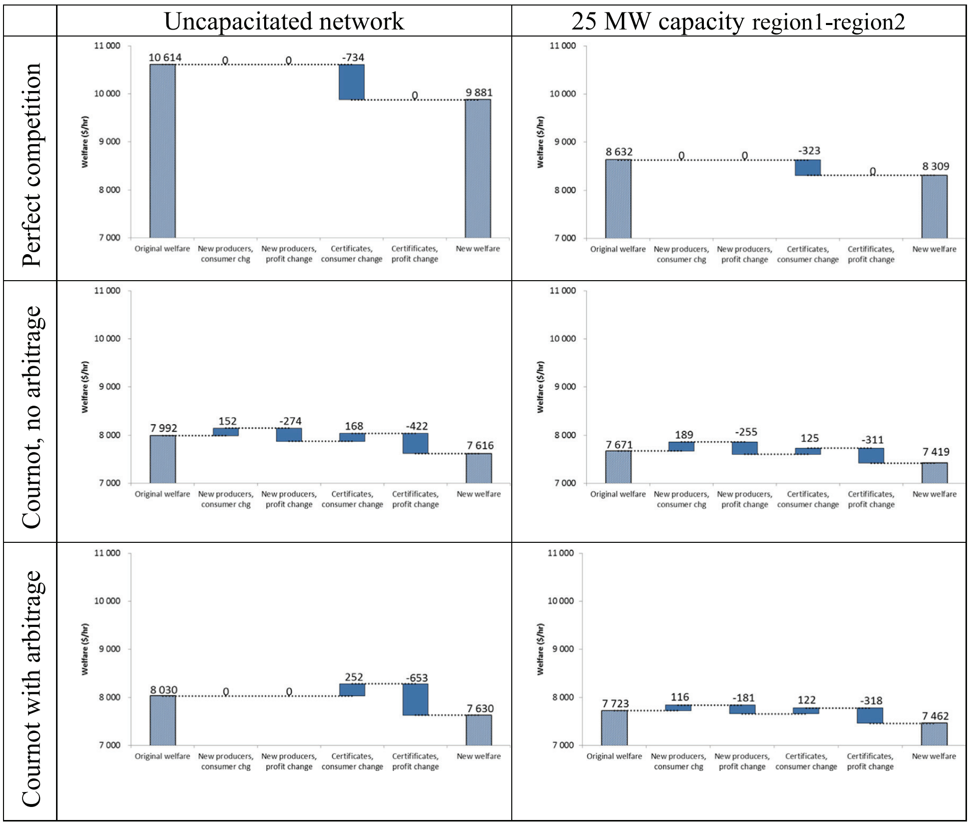

Fig. 7. Decomposed net social welfare effects.

deadweight losses of the support scheme. The capacitated network dampens the impacts compared to the uncapacitated network. Total welfare losses are similar in magnitude for each capacitated case, in contrast to the uncapacitated ones. In the next section we look at a variation where the deadweight losses are shared between consumers and firms.

5.9. Isolated deadweight losses from the support scheme without new players

To further demonstrate the diversity of impacts, we constrain renewable generation to existing firms only and compare the isolated deadweight losses to the situation where we allow new firms. Table 2 shows isolated deadweight losses compared to net social welfare and certificate values. The game outcome becomes the same in each case: Firm 2 should generate the mandatory renewable electricity (but some cases have additional alternative solutions). Thus the isolated social welfare effects from the tradable green certificates are similar in each new case.

In this constrained situation the market competition does not increase, and the deadweight losses are now divided equally between firms and consumers under Cournot competition. It is important to note that consumers do not gain from the support scheme unless new players enter the market (see Table 2). New players are essential in order to improve consumer surplus. Deadweight losses increase, both in absolute terms and relative to welfare. Deadweight losses relative to certificate value however decrease, because the support scheme is more expensive. The deadweight loss is still higher than the total value of certificates in all cases.

The small example shows that a diversity of effects may follow from a tradable green certificate scheme, depending on market competition and network bottlenecks.

6. Conclusions

We present a combined policy model and power market model including network properties from Kirchhoff's circuit laws. We know from previous work that the electric transmission network gives rise to important system effects, and that different forms of market competition have consequences for welfare distribution among market players. In a small example we have demonstrated that both network effects and different forms of market competition give rise to diverse effects of welfare redistribution from a tradable green certificate scheme.

The partial deadweight losses could be substantial. In our example the deadweight losses are higher than the whole value of certificates – each dollar spent on a green certificate would be a direct deadweight loss to society. This extreme result stems from the stylized example, but also realistic deadweight losses may become high, as we will report on in further studies.

The distribution of losses depends on the market power situation. Under perfect competition consumers bear the whole deadweight loss in our example, but this is because firms already have zero profit and thus have nothing to lose. The general picture in Fig. 2 shows that existing firms may lose substantial profits from a green certificate

Table 2
Social welfare losses relative to net social welfare and certificate value.

		Original welfare	certificate value	consumer surplus	profit change	deadweight loss	loss as % of welfare	loss as % of certificate value
Allowing new firms	**Uncapacitated**							
	Perfect competition	10,614	720	-734	-	-734	-6.9 %	-102%
	Cournot, no arbitrage	7,870	140	168	-422	-254	-3.2 %	-181%
	Cournot with arbitrage	8,030	140	252	-653	-400	-5.0 %	-287%
	25MW cap							
	Perfect competition	8,632	320	-323	-	-323	-3.7 %	-101%
	Cournot, no arbitrage	7,605	116	125	-311	-186	-2.4 %	-160%
	Cournot with arbitrage	7,723	140	122	-318	-196	-2.5 %	-140%
Only existing firms	**Uncapacitated**							
	Perfect competition	10,614	720	-734	-	-734	-6.9 %	-102%
	Cournot, no arbitrage	7,992	320	-217	-217	-433	-5.4 %	-135%
	Cournot with arbitrage	8,030	320	-217	-217	-433	-5.4 %	-135%
	25MW cap							
	Perfect competition	8,632	320	-323	-	-323	-3.7 %	-101%
	Cournot, no arbitrage	7,671	320	-217	-217	-433	-5.7 %	-135%
	Cournot with arbitrage	7,723	320	-217	-217	-433	-5.6 %	-135%

scheme. Cournot competition is a milder form of competition where firms are able to exploit market power. The support scheme may offer opportunities for new firms to enter the market. This would increase market competition, and consumer surplus may increase while existing firms lose profit. Even if existing firms are permitted to keep their market power under Cournot competition, they must bear half of the deadweight losses incurred by the support scheme.

The support scheme may also offer opportunitites for new firms to gain at the expense of old firms. The sensitivity analysis indicates that existing firms will not be motivated to compete with new generation capacity.

We draw the conclusion that existing firms will typically bear the biggest burdens from a green certificate scheme. The tradable green certificates may lead to substantial reallocations of welfare from existing firms to both consumers and new firms.

The transmission network has major importance for the localization of new production, and for social welfare redistribution effects from the support scheme. Therefore, the combined model of policy instruments in power markets including system effects from the network proves useful in assessing regionalized effects of the support scheme and evaluating alternative policy instruments promoting production of renewable energy.

Acknowledgements

This work was made possible by the financial support of the Norwegian Research Council through the funding of the project “Regional effects of energy policy” (216513), and by the financial support from Enova SF for the doctoral work of Per Ivar Helgesen.

The authors would like to thank Steven Gabriel, Afzal Siddiqui and Ruud Egging for their valuable comments and suggestions. We also thank two anonymous reviewers for their valuable feedback. Opinions and errors are the responsibility of the authors.

Appendix A. Numerical results and sensitivity analyses

Results from the expanded example are presented in the following tables.

Table 3
Profits and social welfare ($/hr).

			Consumer surplus			Profit					Consumer surplus	Profit	Net social welfare
			Region 1	Region 2	Region 3	Firm 1	Firm 2	New 1	New 2	TSO			
Uncapacitated	Perfect competition	0) Original	3,906	3,906	2,802	-	-	-	-	-	10,614	0	10,614
		a) Certif existing	3,665	3,665	2,550	-	-	-	-	-	9,881	0	9,881
		b) New producers	3,906	3,906	2,802	-	-	-	-	-	10,614	0	10,614
		c) Certif new	3,665	3,665	2,550	-	-	-	-	-	9,881	0	9,881
	Cournot, no arbitrage	0) Original	1,406	1,406	906	3,543	731	-	-	-	3,718	4,273	7,992
		a) Certif existing	1,334	1,334	834	3,391	666	-	-	-	3,502	4,056	7,558
		b) New producers	1,482	1,482	906	3,347	635	9	9	-	3,870	3,999	7,870
		c) Certif new	1,581	1,581	876	2,980	470	64	64	-	4,039	3,577	7,616
	Cournot with arbitrage	0) Original	1,633	1,633	646	3,465	653	-	-	-	3,912	4,118	8,030
		a) Certif existing	1,555	1,555	586	3,313	588	-	-	-	3,696	3,901	7,597
		b) New producers	1,633	1,633	646	3,465	653	-	-	-	3,912	4,118	8,030
		c) Certif new	1,723	1,723	718	2,952	442	36	36	-	4,165	3,465	7,630
25MW $cap_{1,2}$	Perfect competition	0) Original	3,906	2,500	2,038	-	-	-	-	188	8,444	188	8,632
		a) Certif existing	3,786	2,404	1,931	-	-	-	-	188	8,121	188	8,309
		b) New producers	3,906	2,500	2,038	-	-	-	-	188	8,444	188	8,632
		c) Certif new	3,786	2,404	1,931	-	-	-	-	188	8,121	188	8,309
	Cournot, no arbitrage	0) Original	1,586	1,237	906	2,541	1,297	-	-	105	3,729	3,942	7,671
		a) Certif existing	1,509	1,170	834	2,414	1,207	-	-	105	3,512	3,726	7,238
		b) New producers	1,653	1,358	906	2,574	978	-	59	76	3,918	3,687	7,605
		c) Certif new	1,705	1,429	909	2,402	763	9	137	65	4,043	3,376	7,419
	Cournot with arbitrage	0) Original	1,905	1,383	646	2,526	1,167	-	-	97	3,933	3,790	7,723
		a) Certif existing	1,820	1,311	586	2,397	1,079	-	-	97	3,717	3,573	7,289
		b) New producers	1,896	1,472	681	2,551	961	-	19	78	4,050	3,609	7,659
		c) Certif new	1,877	1,576	718	2,450	668	1	117	54	4,171	3,291	7,462

Table 4
Prices ($/MWh).

			Electricity price			Transmission price			Capacity dual	Certificate price	Certificate tax
			Region 1	Region 2	Region 3	Region 1	Region 2	Region 3	R1-R2		
Uncapacitated	Perfect competition	0) Original	15.0	15.0	15.0	-	-	-	-	-	-
		a) Certif existing	15.0	15.0	15.0	-	-	-	-	9.0	0.8
		b) New producers	15.0	15.0	15.0	-	-	-	-	-	-
		c) Certif new	15.0	15.0	15.0	-	-	-	-	9.0	0.8
	Cournot, no arbitrage	0) Original	25.0	25.0	22.3	-	-	-	-	-	-
		a) Certif existing	24.8	24.8	22.1	-	-	-	-	4.0	0.6
		b) New producers	24.6	24.6	22.3	-	-	-	-	-	-
		c) Certif new	23.9	23.9	22.3	-	-	-	-	1.7	0.2
	Cournot with arbitrage	0) Original	23.8	23.8	23.8	-	-	-	-	-	-
		a) Certif existing	23.6	23.6	23.6	-	-	-	-	4.0	0.6
		b) New producers	23.8	23.8	23.8	-	-	-	-	-	-
		c) Certif new	23.2	23.2	23.2	-	-	-	-	1.7	0.2
25MW $cap_{1,2}$	Perfect competition	0) Original	15.0	20.0	17.5	-2.5	2.5	-	7.5	-	-
		a) Certif existing	15.0	20.0	17.5	-2.5	2.5	-	7.5	4.0	0.4
		b) New producers	15.0	20.0	17.5	-2.5	2.5	-	7.5	-	-
		c) Certif new	15.0	20.0	17.5	-2.5	2.5	-	7.5	4.0	0.4
	Cournot, no arbitrage	0) Original	24.1	25.9	22.3	-1.4	1.4	-	4.2	-	-
		a) Certif existing	23.9	25.7	22.1	-1.4	1.4	-	4.2	4.0	0.6
		b) New producers	23.7	25.3	22.3	-1.0	1.0	-	3.0	-	-
		c) Certif new	23.3	24.7	22.1	-0.9	0.9	-	2.6	1.4	0.2
	Cournot with arbitrage	0) Original	22.5	25.1	23.8	-1.3	1.3	-	3.9	-	-
		a) Certif existing	22.3	24.9	23.6	-1.3	1.3	-	3.9	4.0	0.6
		b) New producers	22.6	24.7	23.6	-1.0	1.0	-	3.1	-	-
		c) Certif new	22.4	23.9	23.2	-0.7	0.7	-	2.2	1.7	0.2

Table 5
Demand, generation and transmission (MWh).

			Demand			Fossil production		Renewable production			Flow		
			Region 1	Region 2	Region 3	Firm 1	Firm 2	Firm 2	New 1	New 2	R1-R2	R1-R3	R2-R3
Uncapacitated	Perfect competition	0) Original	312.5	312.5	329.6	954.6	-	-	-	-	318.2	323.9	5.7
		a) Certif existing	302.7	302.7	314.4	839.9	-	*80.0*	-	-	253.3	283.9	30.6
		b) New producers	312.5	312.5	329.6	954.6	-	-	-	-	318.2	323.9	5.7
		c) Certif new prod	302.7	302.7	314.4	839.9	-	*80.0*	x	x	253.3	283.9	30.6
	Cournot, no arbitrage	0) Original	187.5	187.5	187.4	392.2	170.2	-	-	-	74.0	130.7	56.7
		a) Certif existing	182.6	182.6	179.8	383.5	81.6	80.0	-	-	74.0	126.9	52.9
		b) New producers	192.5	192.5	187.4	382.2	160.2	-	15.0	15.0	74.0	130.7	56.7
		c) Certif new prod	198.8	198.8	184.3	362.0	140.0	-	40.0	40.0	74.0	129.1	55.2
	Cournot with arbitrage	0) Original	202.1	202.1	158.3	392.2	170.2	-	-	-	74.0	116.1	42.2
		a) Certif existing	197.2	197.2	150.7	383.5	81.6	80.0	-	-	74.0	112.3	38.4
		b) New producers	202.1	202.1	158.3	392.2	170.2	-	-	-	74.0	116.1	42.2
		c) Certif new prod	207.6	207.6	166.8	362.0	140.0	-	40.0	40.0	74.0	120.4	46.4
25MW $cap_{1,2}$	Perfect competition	0) Original	312.5	250.0	281.1	490.6	353.1	-	-	-	25.0	153.1	128.1
		a) Certif existing	307.7	245.2	273.6	482.0	264.5	*80.0*	-	-	25.0	149.3	124.3
		b) New producers	312.5	250.0	281.1	490.6	353.1	-	-	-	25.0	153.1	128.1
		c) Certif new prod	307.7	245.2	273.6	482.0	264.5	*80.0*	-	x	25.0	149.3	124.3
	Cournot, no arbitrage	0) Original	199.1	175.9	187.4	330.3	232.1	-	-	-	25.0	106.2	81.2
		a) Certif existing	194.2	171.0	179.8	321.6	143.4	80.0	-	-	25.0	102.4	77.4
		b) New producers	203.3	184.3	187.4	334.5	202.7	-	-	37.8	25.0	106.2	81.2
		c) Certif new prod	206.5	189.0	187.7	323.9	179.3	-	13.9	66.1	25.0	106.3	81.3
	Cournot with arbitrage	0) Original	218.2	185.9	158.3	334.9	227.6	-	-	-	25.0	91.7	66.7
		a) Certif existing	213.3	181.0	150.7	326.2	138.9	80.0	-	-	25.0	87.9	62.9
		b) New producers	217.7	191.8	162.5	336.5	206.6	-	-	29.0	25.0	93.8	68.8
		c) Certif new prod	216.6	198.5	166.8	329.8	172.2	-	7.8	72.2	25.0	95.9	70.9

An “x” in Table 5 indicates that renewable production could be distributed otherwise between the firms, thus the solution is indeterminate. We have assumed that Firm 2 generates the renewable quantity.

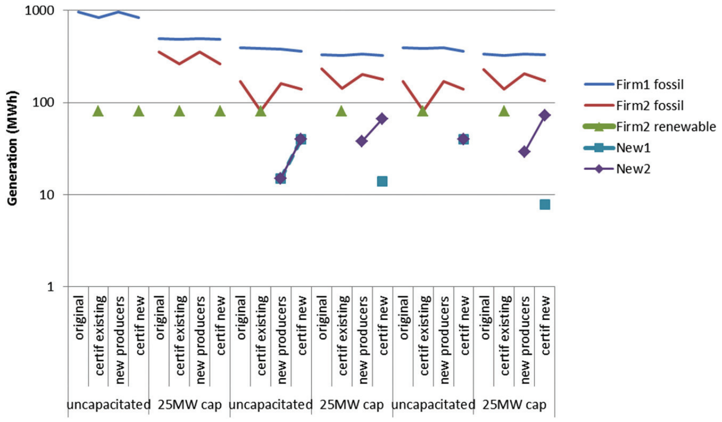

Fig. 8. Generation by case (logarithmic scale).

A.1. Sensitivity analysis of each case

We have seen that new firms will enter the market in cases with Cournot competition green certificates. In this section we investigate production decisions of existing firms if they have *lower* production costs than new firms. We find that marginal production costs must be considerably lower for existing firms to generate new renewable power.

A.1.1. Cournot competition, no arbitrage - Uncapacitated network

What if the existing firms improve their technology, and get a lower production cost? The figure below shows production by firm when we increase production cost for firm $f = 2$ in region 2 (the choice between $f = 1$ or 2 is arbitrary in this case).

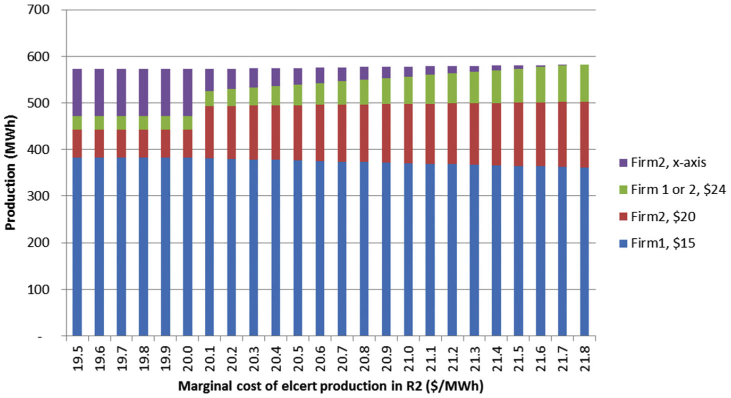

Fig. 9. Equilibrium under Cournot competition without arbitrage in uncapacitated network.

Firm $f = 2$ does not produce any renewable electricity unless the production cost is significantly lower than the new firm's cost of 24. Firm 2 starts generating renewable electricity if the cost comes below the sum of its marginal fossil generation cost and the certificate price (20 + 1.75). If the cost goes down to or below the fossil marginal cost of 20, firm 2 produces only renewable electricity, and more than the certificate quota of 80 MWh. Thus the certificate price is zero. The new firms still produce 30 MWh of renewable electricity in this situation.

Consumers pay a lower price if firm 2’s marginal cost of renewable electricity is above 20:

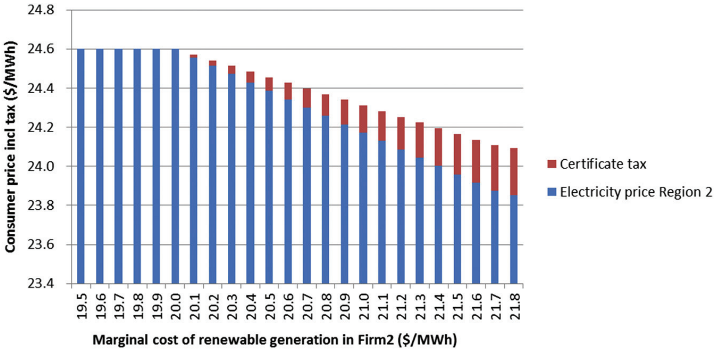

Fig. 10. Consumer price in Region 2.

When the consumer price decreases, the consumer surplus grows – but the firms lose profit and social welfare decreases (as one should expect when marginal production cost increase):

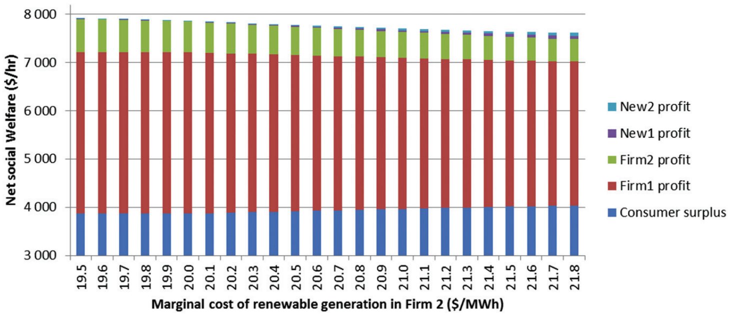

Fig. 11. Net social welfare, Cournot without arbitrage in uncapacitated network.

A.1.2. Cournot competition with arbitrage - Uncapacitated network

An existing firm (let's say firm 2) does not generate renewable electricity unless it is able to decrease its LCOE below the marginal cost of 20 plus the green certificate price of 1.75 as before. A change from the no arbitrage case is that new firms do not generate renewable electricity if the LCOE of firm 2 goes down to 20 or below.

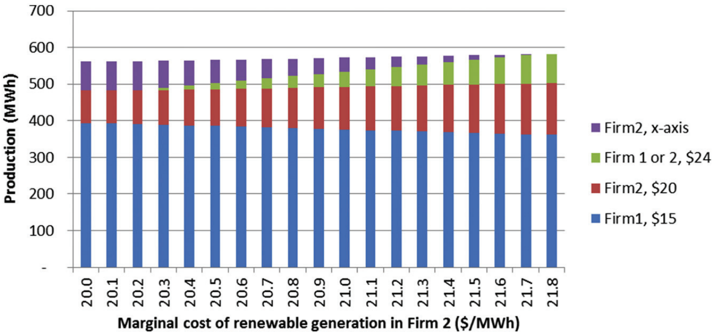

Fig. 12. Equilibrium under Cournot competition with arbitrage in uncapacitated network.

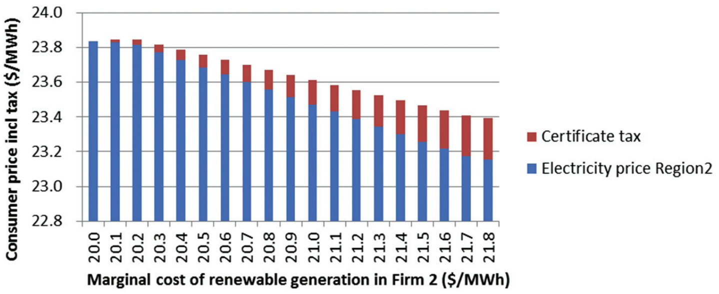

Fig. 13. Consumer price in Region 2.

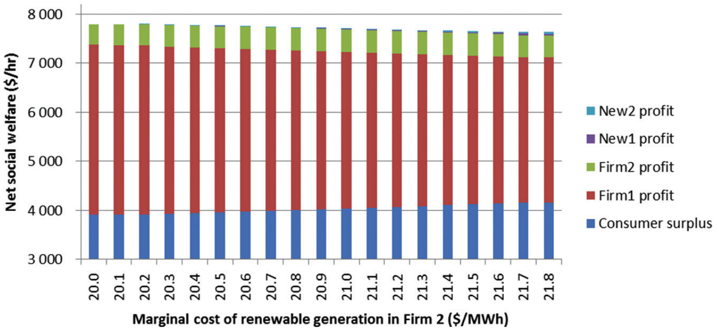

Fig. 14. Net social welfare, Cournot with arbitrage in uncapacitated network.

A.1.3. Cournot competition, no arbitrage - LinkCapacity$_{12}$ = 25

How low LCOE must firm 2 have to generate renewable electricity? If firm 2 has LCOE below 21.45 it starts to generate.

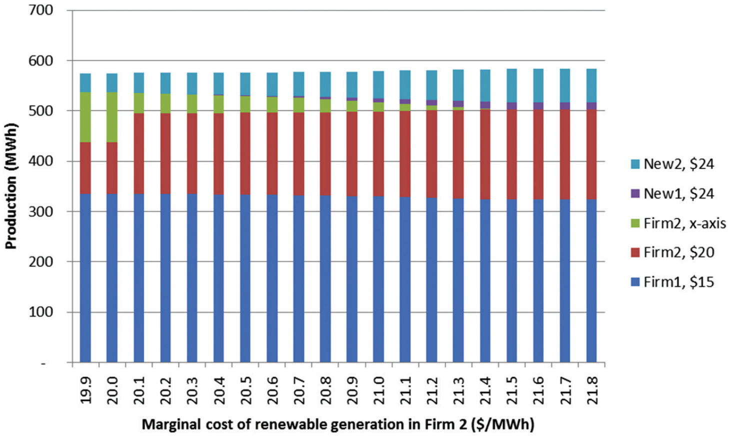

Fig. 15. Equilibrium under Cournot competition with arbitrage in capacitated network.

Again we see the paradoxical picture that consumer price decreases for an increasing firm 2 LCOE cost:

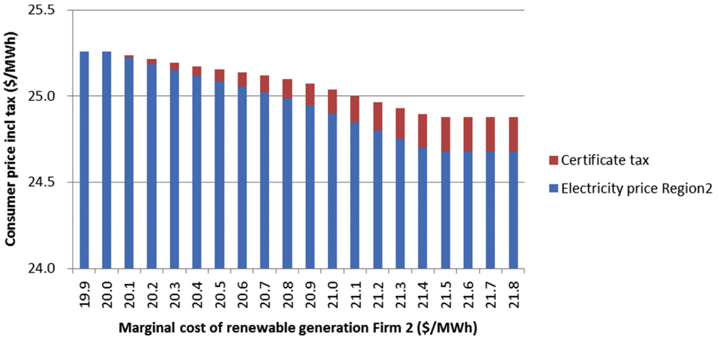

Fig. 16. Consumer price in Region 2.

Thus consumer surplus increases with increasing firm 2 LCOE cost. Existing firms lose profit to new firms in region 2 and then 1. Not surprisingly, net social welfare decreases with increasing LCOE.

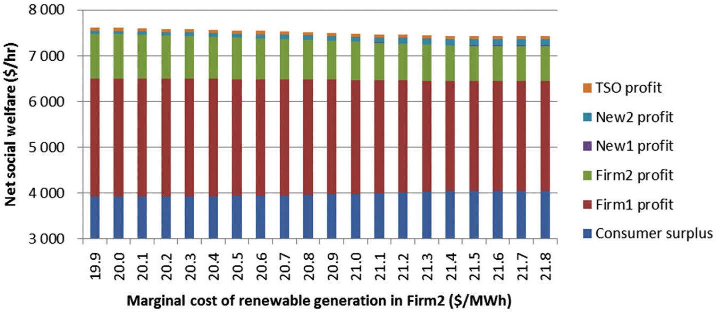

Fig. 17. Net social welfare, Cournot without arbitrage in capacitated network.

A.1.4. Cournot competition with arbitrage - LinkCapacity$_{12} = 25$

How low LCOE must firm 2 have to generate renewable electricity? If firm 2 has LCOE below 21.75 it starts to generate renewable electricity.

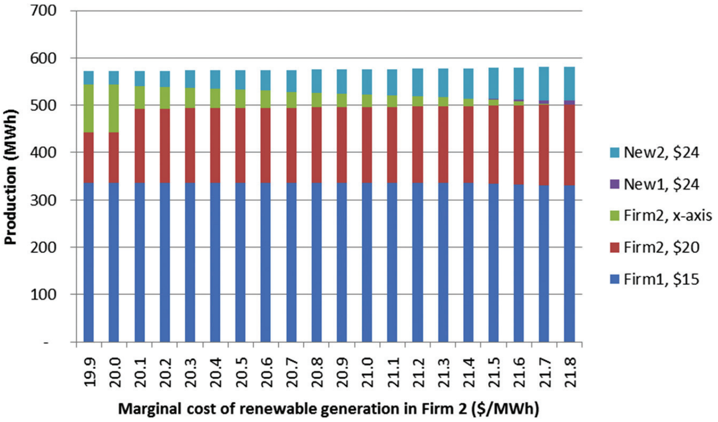

Fig. 18. Equilibrium under Cournot competition with arbitrage in capacitated network.

Consumers in Region 2 would see the following price development.

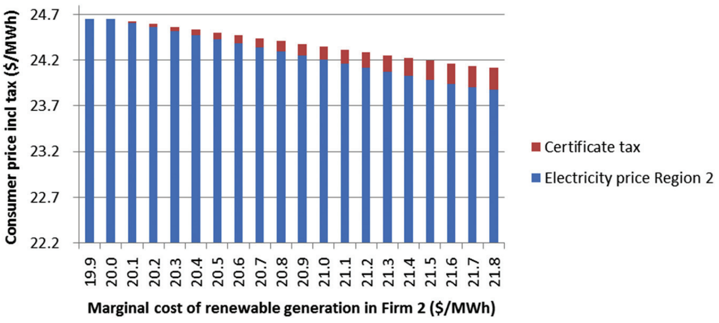

Fig. 19. Consumer price in Region 2.

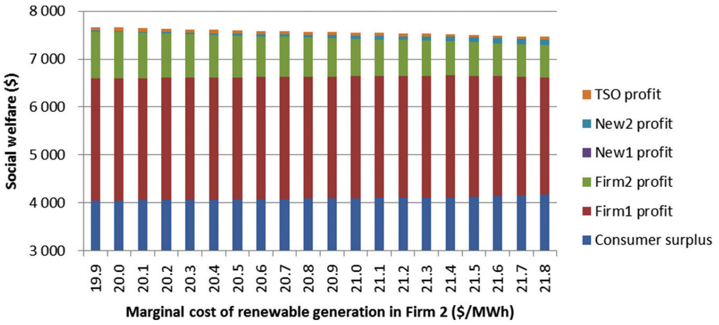

Fig. 20. Net social welfare, Cournot with arbitrage in capacitated network.

References

Bjorndal, M., Jornsten, K., 2007. Benefits from coordinating congestion management - the Nordic power market. Energ Policy 35 (3):1978–1991. https://doi.org/10.1016/j.enpol.2006.06.014.

Böhringer, C., Hoffmann, T., Rutherford, T.F., 2007. Alternative strategies for promoting renewable energy in EU electricity markets. Appl. Econ. Q. 53, 9–30 (Supplement).

Boomsma, T.K., Linnerud, K., 2015. Market and policy risk under different renewable electricity support schemes. Energy 89:435–448. https://doi.org/10.1016/j.energy.2015.05.114.

Borenstein, S., Bushnell, J., 1999. An empirical analysis of the potential for market power in California's electricity industry. J. Ind. Econ. 47 (3), 285–323.

Borenstein, S., Bushnell, J., Kahn, E., Stoft, S., 1995. Market power in California electricity markets. Util. Policy 5 (3), 219–236.

Bushnell, J., 2003. A mixed complementarity model of hydrothermal electricity competition in the western United States. Oper. Res. 51 (1):80–93. https://doi.org/10.1287/opre.51.1.80.12800.

Bushnell, J.B., Mansur, E.T., Saravia, C., 2008. Vertical arrangements, market structure, and competition: an analysis of restructured US electricity markets. Am. Econ. Rev. 98 (1), 237–266.

Coulon, M., Khazaei, J., Powell, W.B., 2015. SMART-SREC: a stochastic model of the New Jersey solar renewable energy certificate market. J. Environ. Econ. Manag. 73:13–31. https://doi.org/10.1016/j.jeem.2015.05.004.

Couture, T.D., Jacobs, D., Rickerson, W., Healey, V., 2015. The Next Generation of Renewable Electricity Policy NREL Technical Report. National Renewable Energy Laboratory, p. 36.

Dahlan, N.Y., Kirschen, D.S., 2012. An empirical approach of modelling electricity prices in an oligopoly market. Power and Energy (PECon), 2012 IEEE International Conference on.

Dirkse, S.P., Ferris, M.C., 1995. The path solver: a nommonotone stabilization scheme for mixed complementarity problems. Optim. Methods Softw. 5 (2):123–156. https://doi.org/10.1080/10556789508805606.

El Kasmioui, O., Verbruggen, A., Ceulemans, R., 2015. The 2013 reforms of the Flemish renewable electricity support: missed opportunities. Renew. Energy 83:905–917. https://doi.org/10.1016/j.renene.2015.05.023.

EU, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the use of Energy from Renewable Sources.

Facchinei, F., Pang, J.-S., 2003. Finite-dimensional Variational Inequalities and Complementarity Problems. Springer, New York.

Gabriel, S.A., Conejo, A.J., Fuller, J.D., Hobbs, B.F., Ruiz, C., 2013a. Complementarity Modeling in Energy Markets. Springer-Verlag, New York.

Gabriel, S.A., Siddiqui, S.A., Conejo, A.J., Ruiz, C., 2013b. Solving discretely-constrained Nash-Cournot games with an application to power markets. Netw. Spat. Econ. 13 (3):307–326. https://doi.org/10.1007/s11067-012-9182-2.

Held, A., Ragwitz, M., Gephart, M., de Visser, E., Klessmann, C., 2014. Design Features of Support Schemes for Renewable Electricity. Ecofys.

Hobbs, B.F., 2001. Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. IEEE Trans. Power Syst. 16 (2):194–202. https://doi.org/10.1109/59.918286.

Hobbs, B.F., Metzler, C.B., Pang, J.S., 2000. Strategic gaming analysis for electric power systems: An MPEC approach. IEEE Trans. Power Syst. 15 (2):638–645. https://doi.org/10.1109/59.867153.

Hobbs, B.F., Drayton, G., Fisher, E.B., Lise, W., 2008. Improved transmission representations in oligopolistic market models: quadratic losses, phase shifters, and DC lines. IEEE Trans. Power Syst. 23 (3):1018–1029. https://doi.org/10.1109/tpwrs.2008.926451.

IEA, 2014. World Energy Outlook 2014. IEA, Paris.

Limpaitoon, T., Chen, Y., Oren, S.S., 2011. The impact of carbon cap and trade regulation on congested electricity market equilibrium. J. Regul. Econ. 40 (3), 237–260.

Limpaitoon, T., Chen, Y., Oren, S.S., 2014. The impact of imperfect competition in emission permits trading on oligopolistic electricity markets. Energy J. 35 (3), 145–166.

Linares, P., Santos, F.J., Ventosa, M., Lapiedra, L., 2008. Incorporating oligopoly, CO2 emissions trading and green certificates into a power generation expansion model. Automatica 44 (6):1608–1620. https://doi.org/10.1016/j.automatica.2008.03.006.

Marchenko, O.V., 2008. Modeling of a green certificate market. Renew. Energy 33 (8):1953–1958. https://doi.org/10.1016/j.renene.2007.09.026.

Metzler, C., Hobbs, B., Pang, J.-S., 2003. Nash-Cournot equilibria in power markets on a linearized DC network with arbitrage: formulations and properties. Netw. Spat. Econ. 3 (2):123–150. https://doi.org/10.1023/A:1023907818360.

Mirza, F.M., Bergland, O., 2015. Market power in the Norwegian electricity market: are the transmission bottlenecks truly exogenous? Energy J. 36 (4), 313–330.

Morthorst, P.E., 2000. The development of a green certificate market. Energ Policy 28 (15):1085–1094. https://doi.org/10.1016/S0301-4215(00)00094-X.

Munoz, F.D., Sauma, E.E., Hobbs, B.F., 2013. Approximations in power transmission planning: implications for the cost and performance of renewable portfolio standards. J. Regul. Econ. 43 (3):305–338. https://doi.org/10.1007/s11149-013-9209-8.

Nagl, S., 2013. The Effect of Weather Uncertainty on the Financial Risk of Green Electricity Producers under Various Renewable Policies. Energiewirtschaftliches Institut an der Universitaet zu Koeln.

Nash, J.F., 1950. Equilibrium points in n-person games. Proc. Natl. Acad. Sci. U. S. A. 36 (1): 48–49. https://doi.org/10.1073/pnas.36.1.48.

Neuhoff, K., Barquin, J., Boots, M.G., Ehrenmann, A., Hobbs, B.F., Rijkers, F.A.M., Vazquez, M., 2005. Network-constrained Cournot models of liberalized electricity markets: the devil is in the details. Energy Econ. 27 (3):495–525. https://doi.org/10.1016/j.eneco.2004.12.001.

Nilsson, M., Sundqvist, T., 2007. Using the market at a cost: how the introduction of green certificates in Sweden led to market inefficiencies. Util. Policy 15 (1):49–59. https://doi.org/10.1016/j.jup.2006.05.002.

Pérez de Arce, M., Sauma, E., 2016. Comparison of Incentive Policies for Renewable Energy in an Oligopolistic Market with Price-Responsive Demand. 37 pp. 159–198.

Perez, A.P., Sauma, E.E., Munoz, F.D., Hobbs, B.F., 2016. The economic effects of interregional trading of renewable energy certificates in the U.S. WECC. Energy J. 37 (4).

Pigou, A.C., 1920. The Economics of Welfare. Macmillan, London.

REN21, 2015. Renewables 2015 global status report. In: Sawin, J.L. (Ed.), Paris: REN21 Secretariat: REN21, p. 251.

Schweppe, F.C., Caramanis, M.C., Tabors, R.D., Bohn, R.E., 1988. Spot Pricing of Electricity. Springer, US.

Stott, B., Jardim, J., Alsac, O., 2009. DC power flow revisited. IEEE Trans. Power Syst. 24 (3): 1290–1300. https://doi.org/10.1109/tpwrs.2009.2021235.

Vespucci, M.T., Allevi, E., Gnudi, A., Innorta, M., 2010. Cournot equilibria in oligopolistic electricity markets. IMA J. Manag. Math. 21 (2):183–193. https://doi.org/10.1093/imaman/dpp004.

Vespucci, M.T., Innorta, M., Cervigni, G., 2013. A mixed integer linear programming model of a zonal electricity market with a dominant producer. Energy Econ. 35:35–41. https://doi.org/10.1016/j.eneco.2011.11.021.

Wei, J.Y., Smeers, Y., 1999. Spatial oligopolistic electricity models with cournot generators and regulated transmission prices. Oper. Res. 47 (1), 102–112.

Wolfgang, O., Jaehnert, S., Mo, B., 2015. Methodology for forecasting in the Swedish-Norwegian market for el-certificates. Energy 88:322–333. https://doi.org/10.1016/j.energy.2015.05.052.

Wu, F., Varaiya, P., Spiller, P., Oren, S., 1996. Folk theorems on transmission access: proofs and counterexamples. J. Regul. Econ. 10 (1):5–23. https://doi.org/10.1007/bf00133356.

Paper II

Efficiency and welfare distribution effects from the Norwegian-Swedish Tradable Green Certificates Market

Paper II

Efficiency and welfare distribution effects from the Norwegian-Swedish Tradable Green Certificate Market

Per Ivar Helgesen and Asgeir Tomasgard
per.ivar.helgesen@ntnu.no (corresponding author), asgeir.tomasgard@ntnu.no
Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management
NO-7491 Trondheim, Norway
July, 2018

Abstract

We investigate economic impacts of the Norwegian-Swedish Green Certificate Market, which promotes electricity produced from renewable energy sources. We formulate a mixed complementarity, multi-region, partial equilibrium model, clearing both the electricity and green certificate markets under perfect competition. The model applies a linearized DC approximation of power flows in the transmission network imposing both Kirchhoff's current and voltage laws in a mixed complementarity formulation suitable for policy analysis.

The certificate scheme combines a subsidy to producers of renewable energy and a tax paid by consumers. The scheme increases the electricity supply and leads to welfare reallocation from old producers to new producers as well as consumers. Consumers pay for the support scheme through a tax, but still benefit in most scenarios due to price decreases in the wholesale markets. The deadweight loss and welfare transfers are reduced when new interconnectors are built or new demand enters the system. We show how geographical distribution effects and locations of new production are affected by the representation of the internal network between the model regions.

Keywords: Renewable energy, Tradable green certificates, Electricity markets, Equilibrium modeling, Cross-border electricity trade, Transmission

1 Introduction

This paper models the use of tradable green electricity certificates (TGC)[1] (MPE, 2011) to support deployment of renewable electricity in the power market. Decarbonized power is a backbone of the clean energy transformation (IEA, 2017), and electricity demand is growing faster than all other final energy carriers (IEA, 2014a). The power sector contributes more than

---

[1] Tradable green electricity certificates (TGC) are also known as Renewable Energy Certificates (REC), Renewable Energy Credits, Renewable Electricity Certificates or Tradable Renewable Certificates (TRC).

any other sector to the reduction in the share of fossil fuels in the global energy mix (IEA, 2014b). Many public support schemes have supported renewable electricity during the last decade, as a way forward to fight climate change, improve security of energy supply, promoting technological development and innovation, and providing opportunities for employment and regional development (EU, 2009; REN21, 2015). The main contribution of this paper is to combine a public support scheme for electricity production with a power market model with isoelastic demand in a capacitated transmission network with cross border energy exchange in order to study the Norwegian-Swedish green certificate market. We employ a deterministic partial equilibrium model to find the cost of reaching a target quota of renewable electricity production. It is formulated as a mixed complementarity, multi-region, partial equilibrium model. Both the electricity markets and the green certificate market are cleared under the assumption of perfect competition.

Our model is calibrated on empirical data from the Nordic power market, and finds an equilibrium solution that quantifies certificate prices in the common Norwegian-Swedish green certificate market as well as regional power prices, power production, demand and power flows through the grid. We study welfare distribution effects between different market participants and between different regions. Producers of new renewable electricity are compensated by green certificates, which they sell to suppliers. The certificate cost is carried further from suppliers to the customers through a certificate tax which affects demand and consumer surplus. The increased electricity supply impacts market prices on electricity, which affects existing producers and consumers.

A main reason behind the support scheme is the EU Renewable Energy Directive that defines legally binding targets for EU member's national renewable energy share (EU, 2009). Policy instruments interferes with the market and will inevitably lead to deadweight losses in the short run market clearing. Market regulations are justified when they can alleviate market imperfections such as externalities, which prevent the market from optimal resource allocation in the long run and maximized welfare. In this case, burning fossil fuels that emit greenhouse gases today may have future societal costs that are not fully reflected in today's prices and not taken into account by market participants. In the case of the Norwegian-Swedish certificate market, the political objective is to increase the renewable share in the energy mix. Our analysis is limited to study the effects of the certificate scheme in terms of welfare loss and distribution effects. We do not look at the long term positive effects or discuss if the suggested targets are justified by these. Still we investigate how two particular situations will change the observed effects: an increase in national demand for electricity and a capacity expansion in transmission to external markets. We do not discuss how these situations may occur or the costs of transmission expansion, but focus on how the certificate scheme affect the investments in generation capacities for renewables and the market clearing in these situations.

The most common policy instruments supporting renewable electricity today are feed-in tariffs, feed-in premiums, tradable green certificates and investment subsidies, possibly combined with tenders in various forms (Butler and Neuhoff, 2008; Held et al., 2014; Menanteau et al., 2003;

Rosnes, 2014). As of early 2015, 73 countries and 35 states/provinces had implemented price-driven feed-in policies, whereas 26 countries and 72 states/provinces had implemented quantity-driven quota policies (REN21, 2015). Tariffs (fixed electricity prices) are decided politically, but the tariff may alternatively be offered as a premium above the prevailing market price of electricity. The feed-in premium is still a price-based support scheme, but the investor also gets exposed to the market price of electricity. This is desirable in terms of operational adaptations to the electricity market (Rosnes, 2014). Tradeable green certificates operate in the opposite manner, a politically determined quantity induces a scarcity premium on renewable generation. The certificate price of renewable generation is formed in a separate certificate market (Morthorst, 2000), and is not defined by a regulator. For each megawatt-hour (MWh) of renewable energy produced, a tradable “green" certificate is issued to the generator, who can then sell the certificate in the marketplace. The demand could be voluntary (based on preferences), or mandatory as a quota obligation on retailers or end-users (Nilsson and Sundqvist, 2007). It is common to design the system as technology neutral in order to promote competition between technologies eligible for certificates, but the system can also be geared towards particular types of renewable energy (Coulon et al., 2015; El Kasmioui et al., 2015). The investor is exposed to the certificate market in addition to the electricity market, making both electricity and certificate cash-flows uncertain. This should increase investment risk, and Jaraite and Kazukauskas (2013) report that firms operating under TGC schemes were more profitable compared to firms operating under feed-in tariff schemes. Feed-in tariffs have a longer track-record than green certificates, and feed-in tariffs will always be the least risky support scheme for the investor (Boomsma and Linnerud, 2015).

From a regulator's perspective, a very attractive property of the tradable green certificate scheme is the potential to minimize the cost of a given quantity of renewable energy (Kildegaard, 2008; Menanteau et al., 2003). Still Butler and Neuhoff (2008) find that German feed-in tariffs have had lower costs and larger deployment of wind power than comparable UK certificate schemes, while Haas et al. (2011) argue that technology-specific feed-in-premiums have an advantage over green certificates the steeper the cost curve is, and that they are easier to implement and revise. The Swedish green certificate scheme is nonetheless reported as the most effective and efficient of all the schemes considered in their study[2]. Aune et al. (2012) show that trade in green certificates can ensure a cost-effective distribution of renewable energy production, but differentiated national targets still prevent a cost-effective distribution of energy consumption across nations (such as in the EU). Pérez de Arce and Sauma (2016) compare four different incentive policies for renewable energy in an oligopolistic market with price-responsive demand. They find that the effectiveness of the different incentive schemes varies significantly depending on the market structure assumed. However, they use a simple network with only two nodes linked by one line where Kirchhoff's voltage law is not relevant. In recent years support instruments are increasingly used in various hybrid policies, especially in combination with competitive bidding (Couture et al., 2015; Held et al., 2014; REN21, 2015).

---

[2] See Figure 10 on page 2192.

Both tradable green certificate scheme and feed-in policies are production subsidies, as opposed to investment subsidies such as investment support and low interest loans. We note that Rosnes (2014) compares operational efficiency under different support policies, and concludes that an inflexible power system should aim to introduce an investment subsidy instead of production subsidies as this does not distort the short term production decisions. In our paper we focus on welfare effects of the established tradable green certificate scheme, and leave further comparisons of support schemes for future research.

Currier and Sun (2014) study market power and welfare in electricity markets employing a tradable green certificate scheme. Instead of considering a deadweight loss from the scheme, they define a social welfare function including a damage function, and calculate welfare maximizing values of the tradable green certificates volume share (optimal renewables policy, ORP) under different market structures. Their work provides insights into the design of the scheme, while we take the TGC goal as a given volume as it is already politically decided. Instead of assuming a damage function in the design, we study the deadweight losses from the scheme. Currier and Sun (2014) do not consider a transmission network in their analysis, while we focus on the spatial properties of the grid that couples the Norwegian and Swedish electricity markets.

According to Oggioni et al. (2012), market coupling is seen as the most advanced market design when restructuring the European electricity market. Tangeras (2015) predicts that electricity exporting countries will choose policies which increase electricity prices, and that a pursuit of domestic objectives distorts transmission investments and thereby market integration below the efficient level. Makkonen et al. (2015) find that national goals in transmission development contradict the Nordic capacity development targets, and conclude that national interests hinders socioeconomic cross-border network investments needed for market integration. Mirza and Bergland (2015) examine whether transmission bottlenecks are truly exogenous, and find that producers in southern Norway may exercise market power and be able to increase market price above marginal cost by inducing transmission congestion during late night and morning hours. These studies indicate that the transmission network is important studying developments of the power market and the green certificate market, and we will show its importance for analysing future welfare effects of the green certificate scheme.

Our model combines inclusion of transmission constraints and investments in renewables, as recommended by Munoz et al. (2013). Exchange of energy between regions is represented with an underlying alternating current (AC) network approximated by a linearized DC network approximation (Schweppe, Caramanis, Tabors, and Bohn, 1988). To our knowledge this is the first study using a model that combines a linearized DC approximation of the AC transmission network with equilibrium modelling of support schemes, and we have used isoelastic demand for electricity. Many policy studies typically make the simplifying but unrealistic assumption that the physical AC network can be modelled as a transport network where the transmission systems operator (TSO) is able to decide transmission quantities individually (as in a network of tradable goods). Notable exceptions are Papavasiliou et al. (2009), Limpaitoon et al. (2011) and Limpaitoon et al. (2014). Papavasiliou et al. (2009) combine a lossless DC-approximated transmission network with two regulatory instruments, either renewable portfolio standards (RPS) or emission taxing. They develop closed form expressions for a 3 node network, with one load and two suppliers with Cournot competition. Limpaitoon et al. (2011) combine an oligopolistic electricity market, a lossless DC-approximated transmission network and a cap-and-trade emissions permits market. They show that market structure and congestion can have significant impact on the market performance. Limpaitoon et al. (2014) proceed further to analyse market combinations in the permits market, and how initial levels of permit allocations influence the results. They show that a firm with more efficient technologies and high levels of initial permits can withhold permits, and that strategic permit trading may influence patterns of transmission congestion. Their model covers a cap-and-trade permits market instead of a green certificate market. The cap-and-trade scheme limits greenhouse gas emissions by creating a cost on emissions, instead of rewarding new renewable generation technologies which do not emit greenhouse gases. The permits lead to welfare redistribution between firms whereas the cost of certificates are transferred to consumers via a tax, thus creating different welfare redistribution outcomes.

Our analysis shows that the AC characteristics of the transmission network directly affects which projects are profitable. AC network properties reduce the flexibility of the grid, so when we include a DC approximation of the AC characteristics in the analysis, the location of new generation projects gets more important. Projects that are less profitable but have a favourable network location are preferred. This leads to higher certificate prices, and higher deadweight losses. Thus, there is a trade-off between transmission network investments made by the TSO to avoid bottlenecks, and the efficiency of the support scheme for renewable power generation. We refer to Helgesen and Tomasgard (2018) for a list of related studies and a further discussion of the importance of modelling the AC characteristics of the transmission network.

International electricity markets have been liberalized and redesigned during the last three decades. Norway was one of the earliest countries, deregulating the electricity market in 1991 (Bye and Hope, 2007). Many studies since then have focused on market competition and possible misuse of market power (Borenstein and Bushnell, 1999; Borenstein et al., 1995; Bushnell, 2003). Although many policies have been implemented to promote competition, there is still evidence of market power in electricity markets (Bushnell et al., 2008; Dahlan and Kirschen, 2012; Mirza and Bergland, 2015; Pérez de Arce and Sauma, 2016).

On the other hand Neuhoff (2003) argues that a system where the system operators integrate national energy spot markets and transmission planning is helpful in mitigating the extent of market power being exercised. Amundsen and Bergman (2007) conclude that the Nordic countries have created an integrated wholesale market that dilutes market power that otherwise would have been a feature of each of the national markets. Amundsen and Bergman (2012) also study to what extent market power on a tradable green certificate market can be used to affect an entire electricity market, and conclude that Swedish producers could exercise market power using the national TGC-market, but that this problem is eliminated by opening the TGC-market for other Nordic countries (which is the current situation).

In this paper we assume perfect competition in the electricity and tradable green certificate markets. In Helgesen and Tomasgard (2018) we presented a similar model for imperfect competition and linear demand, and solve the equilibrium problem consisting of each player's Karush-Kuhn-Tucker (KKT) conditions together with market clearing conditions to obtain a generalized Nash equilibrium. The approach was demonstrated for stylized cases. The main contribution of this paper compared to Helgesen and Tomasgard (2018) is the empirical calibration and identifying the welfare and distribution effects. As compared to the previous paper where we used a linear demand function, we also make more realistic market assumptions using iso-elastic electricity demand as in Böhringer et al. (2007).

Our results from the Swedish-Norwegian green certificate market can be compared with the findings in Fridolfsson and Tangerås (2013) who examine crowding out effects from the green certificate scheme in Sweden, and with Liski and Vehviläinen (2016) who make an empirical analysis of the renewable energy rent transfer from such subsidies in the Nordic market. These relevant contributions have used other methodologies, and we will see that our results are in line with their findings.

The remainder of this paper is organized as follows: Section 2 provides a brief summary of the Swedish-Norwegian green certificate market promoting renewable energy in electricity production. Section 3 describes our mathematical model and the data underlying our quantitative analysis. Section 4 presents the analysis case, section 5 discusses the results and section 6 concludes. An appendix shows how the complementarity model is formed from each player's optimization problem.

2 The Norwegian-Swedish Tradable Green Certificate Market

The common Norwegian-Swedish market for electricity certificates was established on January 1st 2012, nine years after Sweden first introduced their domestic market for tradable green certificates in 2003. In 2012 Norway and Sweden decided to share a combined goal of establishing 26.4 TWh new electricity production based on renewable energy by 2020. This increase amounts to about 10% of the production before the scheme. Norway and Sweden were each responsible for financing 13.2 TWh in the certificate system, regardless of the amount of production that is located in each of the two countries. The contractual commitment for each country was to redeem 198 million certificates by 2035 (198 million certificates amounts to 198 TWh corresponding to 13.2 TWh over 15 years). In 2015 Sweden decided to raise its ambition, and increase the common goal from 26.4 to 28.4 TWh, of which Sweden will finance 15.2 TWh and Norway 13.2 TWh. In 2017 Sweden decided to prolong the scheme, with a unilateral target of increasing renewable electricity production by additional 18 TWh between 2020 and 2030.

Producers receive one certificate per MWh renewable electricity that is generated for a period of 15 years. Electricity suppliers (and certain consumers) have a statutory duty to buy green certificates corresponding to a certain proportion of their electricity deliveries or consumption. Each year the market participants with an obligation to buy green certificates must redeem certificates in order to fulfil their obligation according to the yearly quota. This creates the demand for green certificates. If a market participant cannot redeem the necessary certificates, he is charged a quota obligation fee that amounts to 150 per cent of the volume-weighted average price from the year of obligation. National regulating authorities have provided yearly ratios of the quota obligation until 2035 in national quota curves. However, both supply and demand of green certificates will fluctuate from year to year, and obligation ratios may be adjusted in progress reviews due to new information or preconditions. The first progress review was finalized in 2015, and an adjusted quota curve with updated obligation ratios came into force from 1 January 2016.

Producers that receive certificates earn an income from selling certificates in addition to income from selling electricity. This makes it profitable for investors to invest in new electricity generation from renewable energy sources. The support scheme is technology neutral in the sense that all energy sources defined as renewable energy sources in accordance with Directive 2009/28/EC on the promotion of the use of energy from renewable sources (EU, 2009) qualifies for the right to certificates (MPE, 2012).

Since certificates are only assigned to new renewable production, this support scheme costs less than a subsidy provided to all existing producers would do. Thus the consumer tax that finances this scheme is lower. The downside is that old producers are hurt from the certificate scheme. The electricity certificates will establish additional power production, which will affect the electricity price. This may displace current producers, creating a crowding out effect in the electricity market (Fridolfsson and Tangerås, 2013).

A graphical example of consumer surplus change, producer surplus change, tax financing and deadweight losses is shown in Figure 1 below. We simplify the dynamic matters of the scheme by picturing the certificate and electricity market for one representative year's demand and supply.

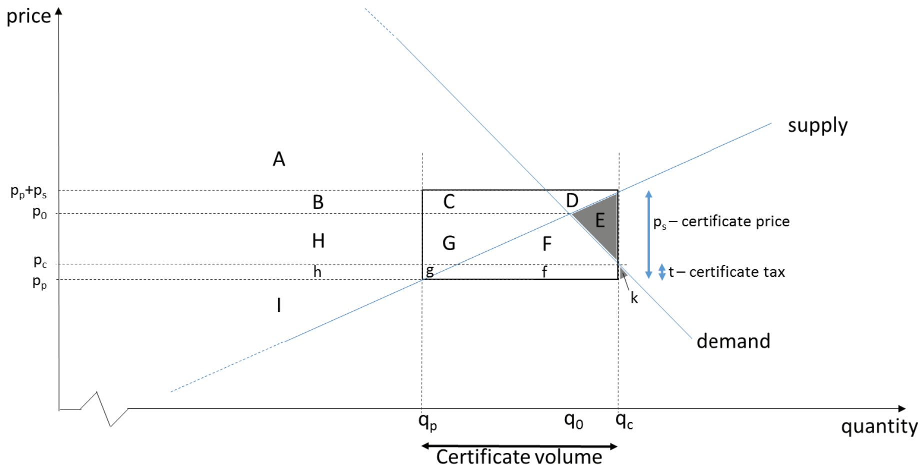

Figure 1 Welfare distribution effects from a certificate support scheme picturing a representative year

The market solution before the green certificate scheme is introduced is found where supply q_0 meets demand at price p_0. The support scheme is going to establish new production by providing the necessary price markup for renewable electricity generation. In Figure 1 we notice that this new generation is crowding out parts of the old generation. The electricity price decreases to p_p, thus remaining old producers receive p_0- $p_p$less than before for each sold unit and reduce their generation to q_p. Renewable generation earns the new electricity price plus the certificate price (p_p+p_s). At this price they choose to produce exactly the target certificate volume of the support scheme. Total production increases from q_0 to $q_c = q_p + \textit{certificate volume}$.

Introducing a financial support scheme to remunerate expensive renewable power generation instead of cheaper (polluting) power generation implies that a welfare loss is imposed to society, unless the climate benefits of the scheme are quantified. Market regulations are justified when they can alleviate market imperfections such as externalities, which prevent the market from optimal resource allocation and maximized welfare. Burning fossil fuels that emit greenhouse gases today may have big future societal costs that are not reflected in today's prices and not taken into account by market participants. Our partial equilibrium model does not capture the benefits of the policy scheme, so introducing the scheme will inevitably result in a welfare loss. These losses are attributed to the policy instruments and are called deadweight losses. The deadweight loss from the green certificate scheme is represented in Figure 1 by the area marked E. In our analyses we investigate who bears these welfare losses. Of course, the motivation for the scheme is that the benefits for society when meeting the overall targets for the green certificate support scheme is higher that the welfare losses in the model. This we do not discuss or analyse.

The support scheme will cost-efficiently deliver new production to the market. Who will gain and who will lose? It is evident that ceteris paribus, the market solution in Figure 1 would imply a significant transfer from old producers (decreasing their producer surplus) to consumers (increasing their consumer surplus), while new producers earn a profit from the combined electricity and certificate income. The area in Figure 1 marked H represents the monetary amount that is shifted from old producer surplus to consumer surplus. The effects can be summarized in Table 1 while Figure 1 shows how the scheme is financed.

Consumer surplus before the scheme:	A	+ B	+ C										
Consumer surplus after the scheme:	A	+ B	+ C			+ F		+ G		+ **H**			
Producer surplus before the scheme:								G	+ g	+ **H**	+ h	+ I	
Producer surplus after the scheme:			C	+ D				+ G	+ g			+ I	
Monetary cost of the support scheme:			C	+ D	+ E	+ F	+ f	+ G	+ g				
Deadweight loss:					E								+ k

Table 1 Summarized effects of the welfare distribution.

A consumer tax is introduced as a markup on the producer price p_p, creating a wedge between producer price p_p and consumer price p_c. The tax is levied by the suppliers in order to cover the supplier's certificate costs and remunerate producers (possibly via brokers). We assume that competition or regulations prohibit suppliers to be overcompensated, thus the total tax amount (areas marked f+g+h in Figure 1) should be equal to the monetary cost of the support scheme (areas marked C+D+E+F+f+G+g in Figure 1). The green certificate tax incurs an additional deadweight loss to society, represented in Figure 1 by the area marked k (a Harberger's triangle).

The consumer tax worsens the loss of old producers. Their total loss is represented by the areas marked G+H+g+h. New producers are not affected much by the tax, since they are compensated by the green certificate price. In Figure 1 consumers are gaining, but the net price effect for consumers is ambiguous. The tax is levied on a much larger volume than the green certificate quota, and the resulting tax could be smaller or larger than the decrease in producer price. Our results will show that both outcomes are possible.

We assume for simplicity in the figure that the tax applies to all consumers, but this does not have to be the case. Energy-intensive industries are for example exempt from this tax in Norway.

This graphical example illustrates some typical welfare distribution effects, but the example is simplified and we need a numerical model to handle a) Different technologies where only new renewable electricity production qualifies for green certificates. b) Dynamics through the year, since both the demand and supply curves change (independently) in different time periods. c) Trade flows between regions, which are affected by transmission capacities.

3 Mathematical model

Our partial equilibrium electricity model is used to analyse green certificate prices in a common transnational market characterized by several sub-regional markets (price areas) connected with several external markets. Green certificate prices are dependent of electricity prices, which have a more granular geographical dimension and a more granular time dimension (hourly prices).

Subnational area prices and transmission constraints are essential for assessing regional effects. We use a lossless approximation of an alternating current (AC) model focusing on real power with linear approximations of the power flow equations – the so-called "DC load flow" model (Schweppe et al., 1988). We have included Kirchhoff's voltage law by a loop rule, instead of using power transmission distribution factor (PTDF) matrices. Net flow (adjusted for line reactances) through any network cycle must be zero. This loop rule model allows us to handle both AC and DC lines in our transmission network, it facilitates future network model improvements like quadratic losses, and other network components like phase shifters and FACTS devices (Bjorndal and Jornsten, 2007; Hobbs et al., 2008).

We have *r* regions and *f* firms. There are *i* generation technologies available, and some of these are eligible for green certificates which are sold in a common market across Norwegian and Swedish regions. A variable levelized production cost is associated with each technology. Each firm can be located in several regions, and operate several technologies. Regions are connected by links with limited capacity. A transport cost and a transport tax is associated with each link.

We optimize social welfare assuming perfect competition and iso-elastic demand for electricity. Under the assumption of perfect competition there will be no arbitrage opportunities, since any price difference must be based on actual cost differences (Hobbs, 2001). Thus we do not consider arbitrage in our model.

We assume that electricity supply is characterized by existing technologies' short-run marginal cost (SRMC), and by the levelized cost of electricity (LCOE) for technologies that require capacity investments (Bertrand competition). Renewable electricity generation receives tradable green certificates according to production volume. We assume that the certificate price is formed such that the combined income from electricity and green certificates covers the LCOE for the last capacity investment that fulfils the quota obligation.

Our model is static in the sense that we consider a yearly quota and a certificate market in equilibrium. We assume that electricity suppliers choose to comply with the quota requirement, instead of paying a quota obligation penalty fee. (Compliance percentage has ranged from 99.95% to 99.99% in 2012-2015). We do not consider dynamic aspects such as banking or borrowing of certificates.

In our study we consider a representative year as our analysis period. We decompose this chosen period into time segments (as in standard capacity expansion models). We do this to capture the diverse operation of the system in different time segments. By splitting the year into timeslices, we can represent typical operating situations in the markets and the transportation network. Both demand and production potential varies over time, and the surrounding markets linked by grid connectors have different variation than the Nordic regions. Consumption, production and flow of power change significantly over the day, week and year.

By introducing timeslices, we also need to recognize the flexibility of hydropower from dammed water reservoirs. Hydro producers take into account the water value in their production decisions, which increases their marginal cost of production (Gebrekiros et al., 2015). Norway and Sweden have considerable water reservoirs which enables producers to shift power generation between timeslices. We model this by allowing flexible production to exceed maximum average production by a factor $(1 + f_i)$, while still restricting yearly production to the total yearly capacity G_{if}. Thus flexible production technologies may shift production between timeslices, but increased production in one timeslice necessarily means reduced production in one or more other timeslices.

The tax condition combines primal (s_{frt}, x_{ift}) and dual variables (μ, t_μ). Since both primal and dual variables are available in the complementarity format, we are able to formulate the tax constraint that finances the support scheme. Without this constraint, we could instead have formulated the max social welfare problem and solved the model as a nonlinear optimization model.

The formulation of the maximum social welfare problem as a mixed complementarity model with a tradable green certificate support scheme financed by a fixed consumer tax, timeslices and flexible production technologies is given below.

Sets

R	regions (we assume that each node represents a region), indexed by *r* and *k*
R_c	regions in the common market for tradable green certificates, indexed by *r*
I	generation technologies, indexed by *i*
I_c	generation technologies eligible for electricity certificates, indexed by *i*
F	electricity producing firms[3], each region is represented by one firm indexed by *f*
F_r	electricity producing firm in region *r*, indexed by *f*
N	loops in electricity network, indexed by *v*
K	lines in electricity network, indexed by (*r, k*)
K_v	lines in loop *v,* indexed by (*r, k*)
T	timeslices, indexed by *t*

---

[3] We do not need a firms index in a perfect competition model, but we choose to define a representative firm in each region to simplify interpretation of the variables and ease a model transition to multiple firms. The *f* index could alternatively represent a region.

Parameters

c_i	marginal cost of production for an existing technology *i*, or levelized cost of electricity for an available new technology *i*
L_{rk}	transport capacity from region *r* to region *k*
R_{rk}	reactance on link from region *r* to region *k*
G_{if}	production capacity of technology *i* in region *f*
k_{rkv}	indicates if line from region r to region k is included in loopflow *v*, takes values *-1, 0* or *1*
Q_{0rt}	reference demand in region *r* in timeslice *t*
P_{0rt}	reference price in region *r* in timeslice *t*
σ	own-price demand elasticity
V	green certificate volume
b	small transport cost on line flow
h_t	hours in timeslice t
H	total number of hours in analysis period
f_i	production flexibility technology i

Variables

s_{frt}	supply from firm *f* to region *r* in timeslice *t*
x_{ift}	production in region *f* using technology *i* in timeslice *t*
z_{rkt}	net flow from region *r* to region *k* in timeslice *t*
p_{rt}	supplier price of electricity in region *r* in timeslice *t*
w_{rt}	(dual) transport cost from the grid into region *r* in timeslice *t*
κ_{vt}	(dual) grid transport cost to impose Kirchhoff's voltage law in loop v in timeslice *t*
τ_{rkt}	(dual) price on grid transmission capacity from region *r* to region *k* in timeslice *t*
φ_{ift}	(dual) price on production capacity in region *f* and technology *i* in timeslice *t*
ω_{ft}	(dual) marginal income in region *f* in timeslice *t*
ψ_{ift}	(dual) price on production flexibility in region *f* and technology *i* in timeslice *t*
μ	price of tradable green certificate
t_{μ}	consumption tax rate to finance the green certificate support scheme

Producer conditions:

$$-p_{rt} + w_{rt} + \omega_{ft} \geq 0 \qquad \perp (s_{frt} \geq 0), \quad f\epsilon F, r\epsilon R, t\epsilon T \qquad (1)$$

$$c_i - w_{rt} + \varphi_{ift} + \psi_{if} - \omega_{ft} \qquad \geq 0 \qquad \perp (x_{ift} \geq 0), \quad i\epsilon I\backslash I_c, r\epsilon R, f\epsilon F_r, t\epsilon T \qquad (2a)$$

$$c_i - w_{rt} + \varphi_{ift} + \psi_{if} - \omega_{ft} - \mu \geq 0 \qquad \perp (x_{ift} \geq 0), \quad i\epsilon I_c \quad, r\epsilon R, f\epsilon F_r, t\epsilon T \qquad (2b)$$

$$\sum_{r\in R} s_{frt} - \sum_{i\in I} x_{ift} \leq 0 \qquad \perp \left(\omega_{ft} \geq 0\right), \quad f\epsilon F, t\epsilon T \qquad (3)$$

$$x_{ift} \leq G_{if}\frac{h_t}{H}(1 + f_i) \qquad \perp \left(\varphi_{ift} \geq 0\right), \; i\epsilon I, f\epsilon F, t\epsilon T \qquad (4)$$

$$\sum_t x_{ift} \leq G_{if} \qquad \perp \left(\psi_{if} \geq 0\right), \quad i\epsilon I, f\epsilon F \qquad (5)$$

TSO conditions:

$$w_{rt} - w_{kt} + \sum_v k_{rkv}\kappa_{vt} + \tau_{rkt} + b \geq 0 \qquad \perp (z_{rkt} \geq 0), \quad (r,k)\epsilon K, t\epsilon T \qquad (6)$$

$$\sum_{f\in F} s_{frt} - \sum_{f\in F_r}\sum_{i\in I} x_{ift} - \sum_{k\in R} z_{krt} + \sum_{k\in R} z_{rkt} = 0 \qquad , \quad w_{rt} \text{ free}, \quad r\epsilon R, t\epsilon T \qquad (7)$$

$$\sum_{(r,k)\in K_v} R_{rk}(z_{krt} - z_{rkt}) = 0 \qquad , \quad \kappa_{vt} \text{ free}, \quad v\epsilon N, t\epsilon T \qquad (8)$$

$$z_{rkt} \leq L_{rk}h_t \qquad \perp (\tau_{rkt} \geq 0), \quad (r,k)\epsilon K, t\epsilon T \qquad (9)$$

Market clearing condition:

$$P_{0rt}\left(\frac{\sum_{f\in F} s_{frt}}{Q_{0rt}}\right)^{-\frac{1}{\sigma}} - p_{rt} - t_\mu = 0 \qquad , \quad p_{rt} \text{ free}, \quad r\epsilon R, t\epsilon T \qquad (10)$$

Tax condition:

$$\sum_{t\in T}\sum_{r\in R_c}\sum_{f\in F} s_{frt}\, t_\mu \geq \sum_{t\in T}\sum_{f\in F}\sum_{i\in I_c} x_{ift}\mu \qquad \perp (t_\mu \geq 0) \qquad (11)$$

Green certificate constraint:

$$\sum_{i\in I_c}\sum_{f\in F}\sum_{t\in T} x_{ift} \geq V \qquad \perp (\mu \geq 0) \qquad (12)$$

The corresponding optimization problem for each player is given in the appendix.

Equation (1), (2a) and (2b) are the equilibrium conditions from the producer's decision variables s_{frt} and x_{ift}. Equation (3) states that the producer cannot supply more power than he produces (Supply constraint). Equation (4) allows flexible production technologies to shift production between timeslices (Flexlim constraint). Equation (5) constrains the yearly production to be within its production limits (Prodlim constraint).

Equation (6) is the equilibrium condition for the TSO's flow variables z_{rkt}. Note that flow variables are nonnegative, so net flow from region *r* to region *k* in timeslice *t* is $(z_{rkt} - z_{krt})$. Equation (7) represents Kirchhoff's current law (KCL constraint). Equation (8) represents Kirchhoff's voltage law (KVL constraint), demanding that net flow adjusted for reactances through any network cycle must be zero. Equation (9) constrains flows to be within the capacity of grid lines (Flowlim constraint).

Equation (10) represents the market clearing condition, such that supply equals demand in each market area and timeslice. Equation (11) assures that the consumption tax rate will finance the green certificates. Equation (12) represents the quantity obligation that regulating authorities have decided for the green certificates.

4 Analysis case

We analyze the effects of the green certificate scheme by comparing future scenarios (just after 2021[4]) with a base scenario that resembles the start of the development period for new renewable electricity production eligible for green electricity certificates. The base scenario defines the starting point for calculating welfare effects for consumers and existing producers. We define three future scenarios and compare four social welfare components against the base scenario. The four components are consumer surplus, profit from existing facilities, profit from new facilities and TSO profit from power flow wheeling fees.

Demand in the base scenario is met by production facilities existing before the green certificate scheme. In future scenarios we assume that new producers manage to cover their investment from their combined sales of electricity and green certificates. In order to invest, the producer must cover both production cost and investment cost – which we combine into the levelized cost of electricity. Electricity is priced such that existing suppliers cover their short-run marginal cost. Green certificates are priced such that new supply exactly reaches the quantity goal of the support scheme and also covers LCOE to the last (marginal) investor. A firm will not invest unless the electricity price plus the certificate price is equal to or higher than its levelized cost of electricity.

Our three future scenarios are constructed by cumulatively introducing

- the green certificate scheme (*elcert* scenario)
- new cables improving grid integration with Northern Europe (*cables* scenario)
- increased demand in Norway and Sweden (*demand* scenario)

The *elcert* scenario builds on the base scenario and forces new electricity supply from renewable energy sources reaching the common goal of 26.4 TWh yearly production in Norway and Sweden. The transmission network is expanded with increased cable capacity to Denmark (Skagerrak 4) which was operational in December 2014.

The *cables* scenario builds on *elcert* but takes into account planned new cables towards Germany and United Kingdom. These cables are expected to become operational in 2020 and 2021 respectively[5]. Norway and Sweden have flexible production and low electricity prices, while neighbouring countries are net importers of electrical power. These factors suggest that producers in Norway and Sweden would benefit from increased cross-border trade over the transmission network.

The third scenario is named *demand*, and builds on *elcert* and *cables.* In addition demand curves are shifted by increasing reference demand by 10% in Norwegian and Swedish price zones. We assume that the increased demand would be willing to pay up to three times the reference price

---

[4] Our future scenarios occur after 2021, because new facilities in Norway must be operational before 31st December 2021 to earn green certificates.

[5] The NordLink 1400 MW HVDC connection to Germany is expected to be operational in 2020, and the North Sea Network 1400 MW HVDC connection to UK in 2021.

P_{0rt}. This upper limit assumption is necessary in order to calculate the change in consumer surplus when the demand curve is shifted. (If we assume that the whole iso-elastic demand curve shifts, then the increase in consumer surplus would be infinite.) The motivation behind the *demand* scenario is that politicians might want to stimulate local demand instead of exporting electricity that have been subsidized by local consumers.

We run these scenarios on two different model versions:

- One simplified model assuming that the grid works as a transhipment network, without taking into account Kirchhoff's voltage law, and
- One version where Kirchhoff's voltage law is imposed on the grid.

If the grid was built with only DC lines it would behave like a transhipment network, while AC lines must adhere to Kirchhoff's voltage law. The actual grid is much more detailed than our aggregated network. It is too strict to assume that the grid adheres to Kirchhoff's voltage law at a highly aggregated level. On the other hand, it is too loose to assume that Kirchhoff's voltage law does not apply. We run our model with Kirchhoff's voltage law to inspect which type of effects that would be lost in a transhipment version of the model.

We define the scenarios listed in Table 1.

Table 1 Scenarios

Scenario description	No Kirchhoff's voltage law	Kirchhoff's voltage law imposed
Base case	`Base`	`Base_kvl`
Green certificate scheme is introduced, increasing the amount of renewable electricity production in Norway and Sweden.	`Elcert`	`Elcert_kvl`
New cables towards Germany and United Kingdom are introduced, increasing the market integration (in addition to green certificate scheme).	`Cables`	`Cables_kvl`
Increased demand – 10% demand increase in Norway and Sweden (in addition to green certificate scheme and new cables)	`Demand`	`Demand_kvl`

4.1 Geographical coverage

Our model covers production and consumption in the 5 nodal price areas of Norway and 4 nodal price areas of Sweden. It also covers cross-border electricity exchange from Norway and Sweden to 8 other price areas (Finland, Denmark West, Denmark East, Germany, Poland, Netherlands, Russia, UK). The resulting network has 17 nodes and 24 arcs, of which 16 are AC lines and 8 are DC lines. The network is shown in Figure 2, in which AC lines are black and DC lines are yellow. The planned cables towards Germany and United Kingdom (included in the Cables and Demand scenarios) are indicated with dashed lines.

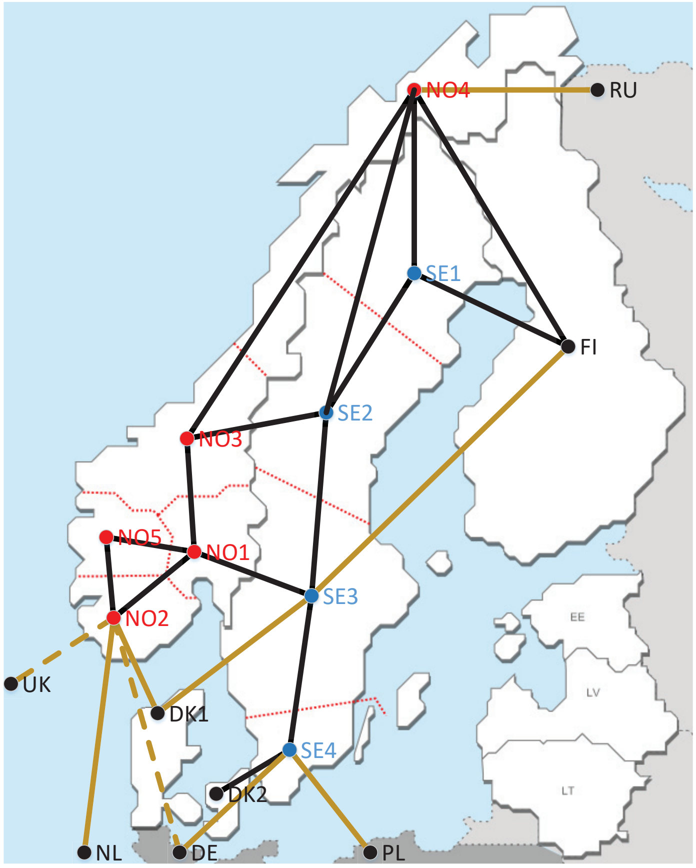

Figure 2 Transmission network. AC-lines in black, DC lines in yellow, planned lines are dashed.

12 nodes are connected in the AC network with 16 arcs. This gives rise to 16-12+1=5 cycles in the AC network.

4.2 Production technologies

Table 2 shows the power generation technologies included in the model, and their relevant SRMC and LCOE costs.

Table 2 Technology parameters

		SRMC [kNOK/GWh]	Investment (I) [kNOK/MW]	Fixed operating and maintenance (F) [kNOK/MW]	Lifetime (T) [years]	Availability factor (a) [share]	LRMC [EUR/GWh]	LCOE [EUR/GWh]
Existing	HYDREG0	5,00	1	1	40	0,95	0,64	0,65
	HYDROR0	6,00	1	1	40	0,95	0,77	0,78
	WIND0	10,00	1	1	20	0,32	1,30	1,31
	NUCLEAR0	50,00	1	1	40	0,82	6,27	6,28
	THERMAL0	250,00	1	1	25	0,94	31,27	31,27
Fossil	NGCC	518,00	6 300	160	25	0,86	75,63	79,07
	NG02CO2	521,00	13 071	360	25	0,86	88,17	95,45
	NG01	850,00	4 455	135	25	0,87	114,20	116,72
	NGPEAK_101	916,00	4 455	150	25	0,17	156,04	169,18
New hydro	HYDRUN04	12,00	10 800	85	40	0,60	19,82	31,23
	HYDRUN05	13,00	15 300	205	40	0,40	43,57	69,69
	HYDREG07	11,00	13 000	300	40	0,95	18,27	28,79
	HYDREG_101	14,00	17 500	420	40	0,95	24,74	39,05
	HYDRUN_101	15,00	15 000	180	40	0,50	34,17	54,29
	BIO	15,00	20 000	300	25	0,57	48,77	63,60
wind	WIND_on1SE	16,00	10 800	300	20	0,33	57,67	67,75
	WIND_on2SE	17,00	10 800	350	20	0,32	62,02	72,86
	WIND_on3SE	18,00	12 000	350	20	0,31	69,20	81,32
	WIND_offSE	19,00	20 970	350	20	0,42	81,03	95,27
	WIND_offNO	20,00	28 840	350	20	0,43	101,66	119,60
wind projects	W1A107N2	12,36	9 236	376	20	0,39	45,20	53,11
	W2A128N3	15,44	9 395	348	20	0,29	60,26	70,82
	W3A112N4	15,44	9 555	426	20	0,35	53,26	62,55
	W4A111N5	8,24	9 561	265	20	0,41	39,47	46,43
	W5A108N2	12,36	9 797	400	20	0,41	45,16	53,05
	…	…	…	…	…	…	…	…

Data sources: (Nohlgren et al., 2014; Sidelnikova et al., 2015)

Data for 123 potential Norwegian wind power projects are included in the analysis, the source is (IFE/NVE, 2014). The intermittency of wind power is covered entirely by the availability factor *a*. The formulas for calculating long-run marginal cost (LRMC) and LCOE are given in the appendix.

Existing production facilities available in the base scenario are depicted per area and technology in Figure 3.

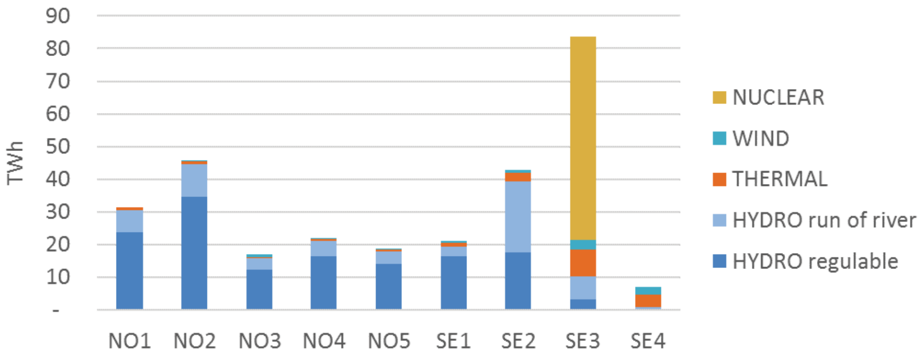

Figure 3 Existing technologies

Capacities of available technologies per area are presented in Table 4 in the appendix.

Regulable hydropower producers are able to shift generation between timeslices. We allow such technologies to exceed their maximum average production by a factor $(1 + f_i)$. Reservoirs in Norway are rather large, and based on the calibration of prices and flows per area and timeslice we have used a value of $f_i = 4$, which produces model results that match well with what we observe in the market. This flexibility parameter could be scaled according to reservoir capacity in the area. The parameter could also be depending on the timeslice, due to seasonal hydro inflow and reservoir levels. Such parameter improvements are left for future work.

4.3 Characteristics of market demands in Norway and Sweden

The electricity consumption depends on many factors, for example temperature, business hours and electricity price. In our study we calculate regional electricity demand for a representative base year and a future year. We divide the year into timeslices in order to represent different temperature and activity levels.

We represent a price dependent demand in each price area of Norway and Sweden by a regional isoelastic demand function $Q_{rt} = Q_{0rt}\left(\frac{p_{rt}}{P_{0rt}}\right)^{\sigma}$, where we have calculated reference demand Q_{0rt} and reference price P_{0rt} as consumption and price averages from hourly observations 2012-2014 for each region and time-slice in the model. Figure 4 shows hourly observations of daytime electricity consumption and price in South Norway during 2014 for different seasons.

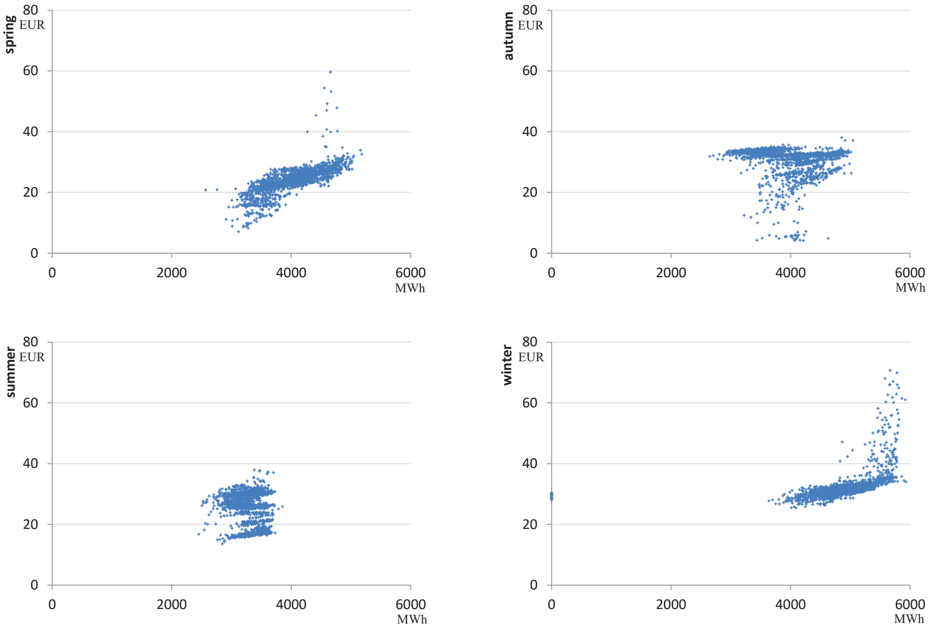

Figure 4: Electricity consumption in southern Norway (NO2), 2014, daytime. Source: NordPoolSpot

We notice that prices and consumption differs a lot during the year. 2014 prices were unusually low during spring, while consumption levels were the lowest during summer. Both prices and consumption were high during winter. We do not see a clear relationship between consumption and price in Figure 4. First, this is because other variables also affect the consumption. Much of the electricity is used for heating, and temperature is an important explanatory variable (Holstad and Pettersen, 2011). Second, eelectricity spot prices are decided day-ahead based on prognosticated consumption and production, and few consumers are aware of the electricity price at the actual time of consumption. This suggests inelastic demand with a low (close to zero) own-price short-run elasticity. On the other hand, we know that price increases quickly raise media attention and public awareness, suggesting a relationship with a more negative long-run elasticity over weeks, months and years. Deployment of smart meters and improved demand side management may also change the consumer behavior in the future, resulting in more elastic demand (more negative own-price elasticities).

Empirical estimates of electricity own-price elasticity show inelastic short-run demand and more elastic long-run demand. Lijesen (2007) estimates a short-run elasticity of −0.029 based on hourly Dutch data, and reports long term estimates from other studies in the range from −0.1042 to −3.39 [6]. Azevedo et al. (2011) use annual data and estimate long-run own-price elasticities ranging from −0.2 to −0.25. Johnsen (1998) estimates the price elasticity in the Nord Pool power market to be between −0.5 and −0.35. Hjalmarsson (2000) estimates a long-term own-price elasticity in the Nord Pool power market of −0.039. Holstad and Pettersen (2011) estimate an elasticity of −0.05 based on monthly data from January 1996 to December 2010. They also report estimates based on rolling regressions in the range from 0 to −0.12 (see figure 4.2 on page 17). We have assumed an own-price demand elasticity of $\sigma = -0.1$ for all the Norwegian and Swedish price areas. The same value is used in Qi (1997) and Limpaitoon et al. (2014), while Hobbs et al. (2008) assume more elastic demand with price elasticity of −0.4 in the competitive price-quantity points of the linear demand curves.

4.4 Timeslices

Electricity demand, production and power flows vary significantly over the day, week and year. We divide the year into separate intervals representing demand characteristics and operating modes of the transmission network. Based on observed hourly consumption and power flows through the transmission network, we define timeslices by calendar season and night versus day.

Figure 5 shows the average net flow of electricity into Norway and Sweden with these timeslices. We see that there is a seasonal pattern, and that the flow into Norway and Sweden have different levels at day versus night.

---

[6] See Table 1 on page 251.

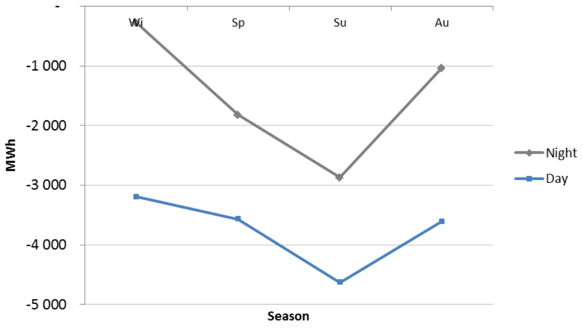

Figure 5 Average flow of electricity into Norway and Sweden by season and day/night. Source: NordPoolSpot

Figure 6 shows the average electricity prices per timeslice in East-Norway NO1 (which closely resembles NO2 and NO5) and Mid-Norway NO3 (which closely resembles NO4). We recognize the same seasonal pattern, and the price difference between day and night.

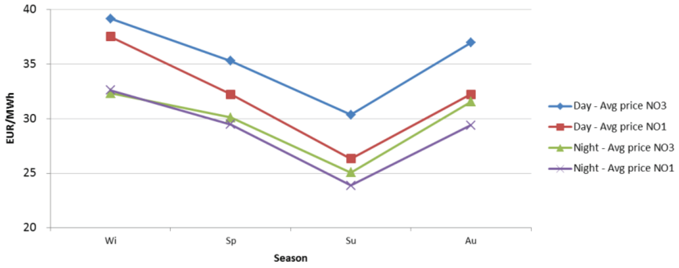

Figure 6 Average prices in NO1 and NO3 by season and day/night. Source: NordPoolSpot

Our model operates with reference prices P_{0rt} per area r and timeslice t. We use the observed timeslice averages as reference price and reference demand. Reference prices per area for each timeslice are shown in figure 17. Reference prices and quantities are given in Table 6 in the appendix.

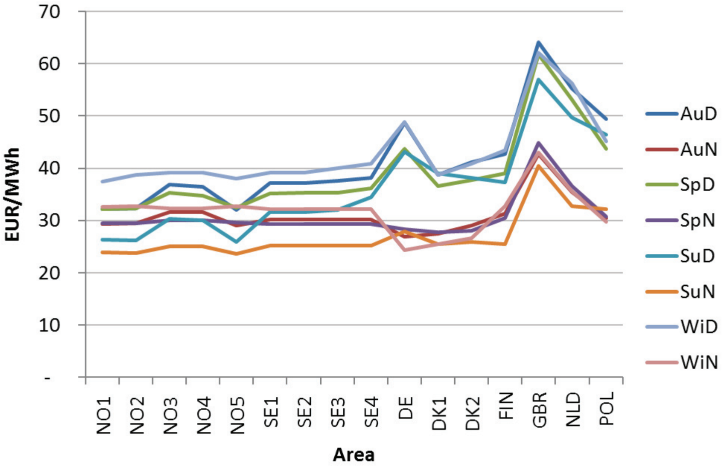

Figure 7 Reference prices per area and timeslice

4.5 External markets

We assume that cross-border cable capacities are sufficiently small to not affect market prices outside Norway and Sweden. All prices outside Norway and Sweden are kept constant at their reference price in all scenarios. Thus we assume that electricity can be exported within the cable capacity without reducing the price in the receiving area. We also assume that electricity is available to be imported at the external reference price within the cable capacity.

4.6 Transmission characteristics

Our model operates on an aggregated network. Capacities of the included lines are net transfer capacities (NTC) collected from ENTSO-E (2014). The physical network may have parallel lines which we represent as one. Thus the physical laws do not necessarily apply directly in our network representation. Line capacities of NO2-DK1, NO2-DEU and NO5-GBR are adjusted in different scenarios. We assume that most of our aggregated transmission lines have identical reactance, but we reduce reactance for SE1-SE2 and SE2-SE3 by 25% to obtain solvable and realistic flows in the network. The transmission values we have used are presented in Table 5 in the appendix.

4.7 Implementation

The model has been programmed in GAMS (Bussieck and Meeraus, 2004), and the mixed complementarity problem has been solved with the PATH solver (Dirkse and Ferris, 1995).

The model is solved successively in three steps. In the first step we solve a simplified optimization model without considering the green certificate scheme. Second we solve the complementarity model with linear demand. Ultimately we solve the complementarity model with isoelastic demand. This solve procedure was chosen in order to obtain initial starting points and help the solver to efficiently find a solution.

5 Results

The Norwegian-Swedish Green Certificate scheme will provide an increased amount of electricity production in Norway and Sweden, which will influence market prices by pushing prices downwards. Consumers must finance the certificates by a tax, but electricity price reductions may still increase the consumer surplus. The welfare effects of the green certificate scheme depend heavily on which future scenario that will manifest itself, but also on the geographical location of the individual actors.

In the base scenario electricity prices in Norway and Sweden are formed from internal thermal production, import from Finland during autumn night and summer day, and import from Denmark and Netherlands during summer night. Internal transport capacities between areas and production flexibility between time-slices make the area prices even out during most of the year.

Figure 8 shows average yearly electricity prices per area in different scenarios.

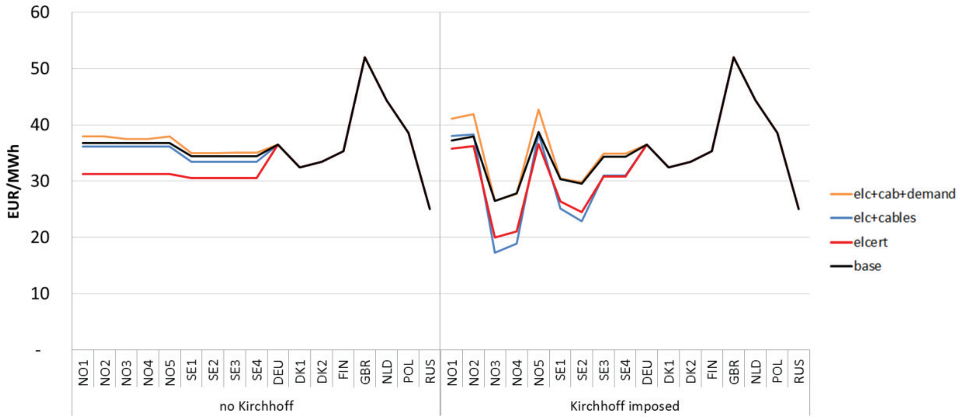

Figure 8 Average regional prices in different scenarios with and without Kirchhoff's Voltage Law imposed

When we impose Kirchhoff's voltage law, we get significant regional price differences. The northern price areas (NO4, NO3, SE1 and SE2) form considerably lower prices than the other areas in all scenarios. These areas have low consumption and net power export (with NO3 as an exception, but NO3 has sufficiently high inflow capacity from NO4 to inherit these properties). Less realizable grid capacity under Kirchhoff's voltage law leads to bottlenecks on connections towards the south, more lock-in of electricity in the north and thus lower prices.

Introducing the green certificate support scheme (*elcert* and *elcert_kvl*) leads to significant decrease in electricity prices compared to the *base* and *base_kvl* scenarios. Consumers benefit from this, while existing producers lose significantly. Old suppliers lose from 1.2 to 1.6 billion euros yearly, compared to the situation before the scheme (see Figure 9 below and Table 7 in the appendix). Consumers on the other hand increase their consumer surplus by 270 to 620 million euros each year, thanks to the decrease in electricity prices. The deadweight loss of the scheme is substantial in these scenarios: 36% of the support scheme cost is lost in total welfare reduction[7] when we do not consider Kirchhoff's voltage law. With Kirchhoff's voltage law imposed, the grid is less flexible and network capacities are harder to utilize. The geographical location in the grid becomes more important, and expensive projects with favorable grid locations improve their competitiveness. As a result, deadweight losses from the green certificate scheme increase to 43% of the support scheme cost when Kirchhoff's voltage law is imposed.

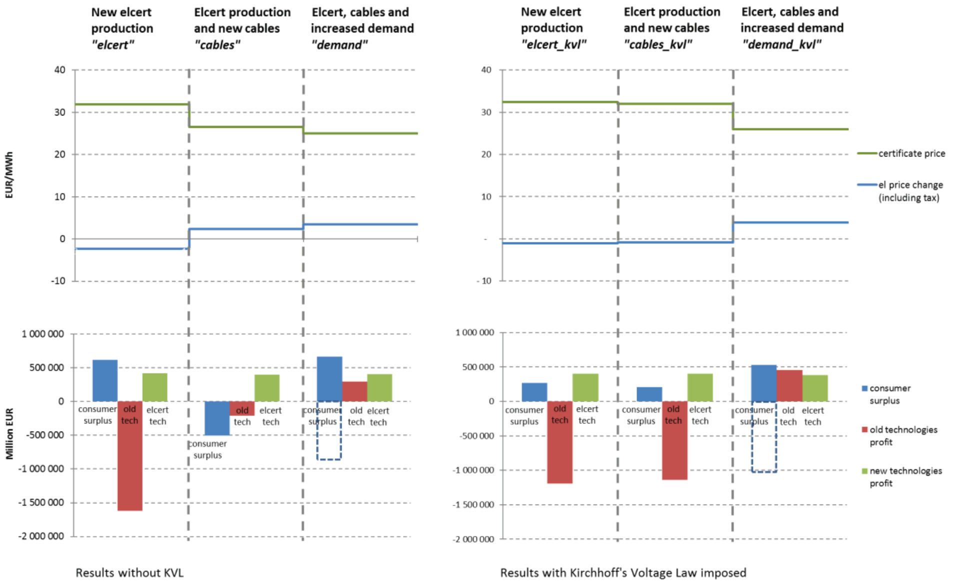

Figure 9 Certificate price, average electricity price change and welfare redistribution in different scenarios compared to base case

---

[7] We address welfare reduction as calculated in the partial equilibrium model, not considering the unquantified welfare increase from the increased share of renewable electricity.

New producers (who receive green certificates) earn around 400 million euros yearly in the *elcert* scenario, and they earn about the same profit in each scenario. The different scenarios have much greater welfare distribution impacts for old suppliers, consumers and the TSO, than for new producers. The reason is that the electricity price and the green certificate price complement each other as shown in Figure 9, providing similar income for new producers in every scenario.

When new *cables* become available, the impact of Kirchhoff's voltage law on grid behaviour is evident at the aggregate level. When we do not consider Kirchhoff's voltage law, electricity prices increase from the *elcert* scenario, and the green certificate price decreases (see Figure 9). Existing producers still earn reduced profits compared to the base case (210 million euros less), but they benefit from the increased integration towards Northern Europe. Local consumers pay higher electricity prices (plus the certificate tax), and the consumer surplus decreases by 500 million euros yearly. New producers earning electricity certificates get similar profits as in the *elcert* scenario (400 million euros yearly), since changes in electricity and certificate prices are counteracting each other. Nonetheless there are different geographical outcomes between the two scenarios, since different production facilities are built due to network effects (see Figure 14).

When we include Kirchhoff's voltage law (scenario *cables_kvl*), we get similar welfare distribution effects as in the *elcert_kvl* scenario on the aggregated level shown in Figure 9. Electricity prices do not change much on average, but there are regional differences which we will return to. The grid is less flexible when Kirchhoff's voltage law is imposed. Higher prices abroad does not carry over to the southern regions in Norway and Sweden like in the *cables* scenario without KVL. In the *cables_kvl* scenario the TSO collects the welfare increase from new cables towards northern Europe (see Figure 11).

The TSO is a winner in both *cables* scenarios, increasing yearly profits by 400 to 490 million Euros (see Table 7). The positive effects from the new cables outweigh the deadweight loss from the green certificate scheme, so the combination of the scheme and cables is more efficient. We must however take into account the costs of new cables. These are not included in our model calculations[8].

Most of the production increase in these scenarios is exported from Norway and Sweden. When new cables become available, yearly net export increases *more* than production increases. Consumers in Norway and Sweden end up subsidizing new power production which gets exported to consumers in other countries. The increased local demand in the *demand* scenarios counteracts this effect. Export volumes are reduced significantly, but local electricity prices increase – particularly in the *demand_kvl* scenario. The certificate price decreases, and the certificate tax for consumers gets reduced. All four actors (consumers, old producers, new

---

[8] Both the Nordlink and the North-Sea Network cables are expected to cost 1.5-2 billion Euro, and the Norwegian TSO owns 50% of both. The TSO increases yearly profits by 0.34 billion Euro, which means that the investment is recovered after 5-7 years assuming a 5% discount rate.

producers, TSO) are gaining in these scenarios. Thanks to higher prices, old producers are able to increase their profits by 300 to 460 million euros compared to the base scenarios. Consumers are also better off, thanks to the shift in the demand function. With the original demand function, consumer surplus would instead have decreased by 870 to 1010 million euros, which is more than the certificate value of the scheme (this is indicated in Figure 9 by the dashed "ghost" bars).

Our results show that consumers benefit in most scenarios, despite paying for the support scheme. Liski and Vehviläinen (2016) reach the same qualitative result. They find that going from 0% market share of wind power in 2001 to a 5% market share amounting to 20 TWh of wind power in 2014 reduces prices by 28 %. Increasing the market share further by 26 TWh would produce a further price reduction of about one third. However, they assume inelastic demand and include no export or import from the Nordic market. Our results indicate that 26.4 TWh of new renewable electricity leads to around 15% price decrease. Consumer willingness to pay for subsidies is estimated to exceed actual paid subsidies, thus consumers benefit from the scheme in both papers.

The net social welfare redistribution effects for each geographical area is shown in Figure 10 (we do not consider TSO profit here). Only two regions have positive net social welfare change in the *elcert* and *cables* scenarios, all the other areas carry a loss. The NO5 area has a positive net social welfare change in all scenarios. The reason is that NO5 gets green certificates from highly profitable new hydro generation. The SE3 area has the highest consumption and production, and thus the largest variation between scenarios. SE3 has substantial losses in the *elcert* and *cables* scenarios, but the biggest welfare gain in the *demand* scenarios. We see that there are wide ranges of outcomes for several regions, for example NO2 and SE2 which may experience considerable decreases of net social welfare.

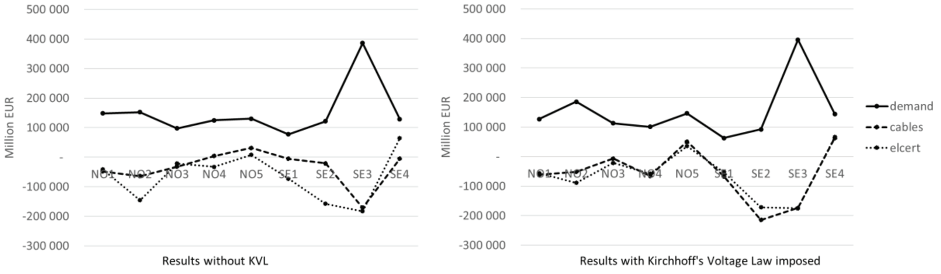

Figure 10 Regional net social welfare change

The regional welfare effects on this aggregation level are quite similar, regardless of whether Kirchhoff's voltage law is imposed or not. The distribution of welfare between market players is however strongly dependent of the grid flexibility. If we do not consider Kirchhoff's voltage law, the distribution between players is homogenous across regions in all scenarios. Changes in old producer profits and consumer surplus have the same sign in each region for each scenario. We refer to Figure 23 to Figure 25 in the appendix for separate welfare components and TSO profits.

Imposing Kirchhoff's voltage law creates disparities between players in different regions. Electricity prices in east, south and west Norway (NO1, NO2 and NO5) do not decrease as much in the *elcert_kvl* scenario, and increase more in the *demand_kvl* scenario. Due to these price movements, consumers in NO1, NO2 and NO5 consistently lose consumer surplus in all kvl-scenarios. This effect is apparent in Figure 11, which shows welfare change for each actor in the *cables-kvl* scenario. Electricity prices decrease in all other areas, and consumers gain while existing producers lose. Old producers in SE3 are crowded out, and reduce their generation by 4 TWh. The TSO profit increases significantly, thanks to increased power transfer volumes in an inflexible grid.

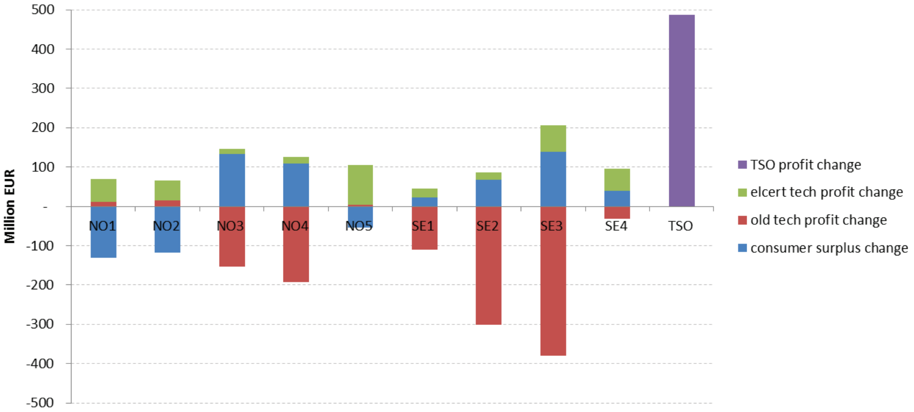

Figure 11 Geographical welfare distribution effects going from *base* case to elcert scheme with new *cables* towards Europe with Kirchhoff's voltage law imposed (cables_kvl scenario)

NO5 and SE4 are the only regions that experience a net positive welfare change. Consumers in NO5 lose surplus and old producers gain, while the outcome in SE4 is opposite. Figure 26 and Figure 27 show similar regional disparities in scenarios *elcert_kvl* and *demand_kvl*.

5.1 Certificate prices and new generation investments

Our results indicate that certificate prices need to be in the same range as electricity prices in order to facilitate new renewable production to fulfil the goal of the support scheme, see Figure 12.

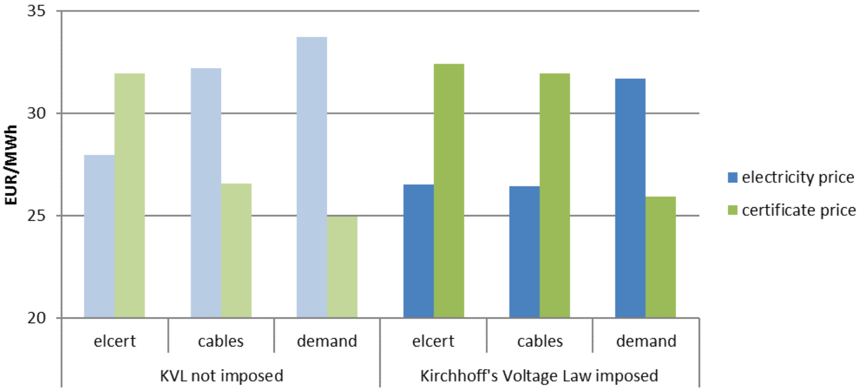

Figure 12 Certificate and electricity prices by scenario

Each scenario has a positive certificate price, and thus reaches the production goal of the support scheme exactly. Figure 13 shows the amount of each generation technology by scenario. The different technologies are sorted by increasing LCOE (except onshore wind in Norway, which consists of a group of different projects with individual LCOE costs). The most expensive renewable technology is defining the certificate price in each scenario.

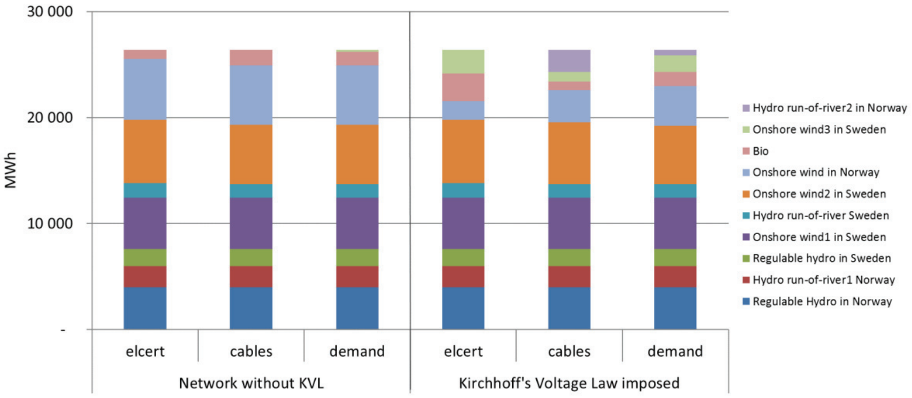

Figure 13 Production technologies by scenario

As a starting point a project's LCOE determines whether that project will be developed (assuming adequate local demand or network capacity). When new cables and increased local demand are introduced, the geographical location of each project becomes increasingly important. More expensive technologies are developed when Kirchhoff's voltage law is imposed, and the different scenario assumptions affect the usage of technologies more. The reason is that transmission network capacities becomes less flexible, and the project location matters more.

Figure 14 shows the variation in renewable electricity expansion between the different scenarios. New cables make electricity prices increase, and bio projects in SE3 and SE4 become profitable. When local demand also increases, more expensive wind projects in SE4 are developed (wind 3 in Figure 14).

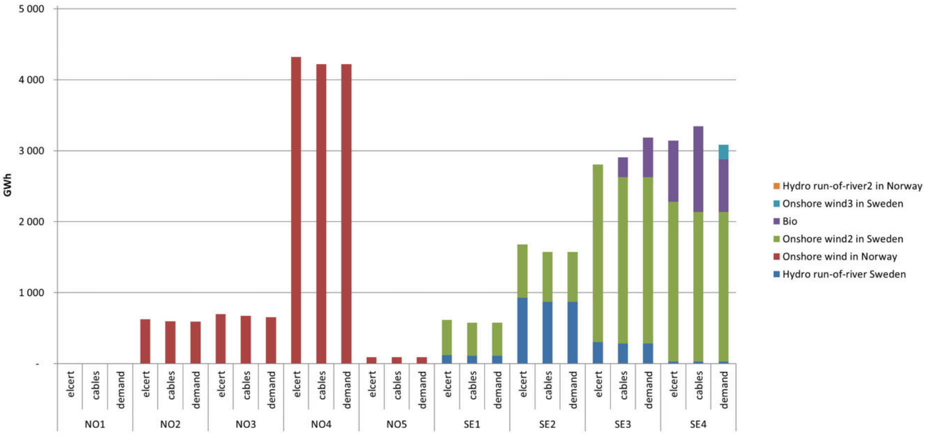

Figure 14 Green certificate generation by region and technology, Kirchhoff's voltage law not imposed

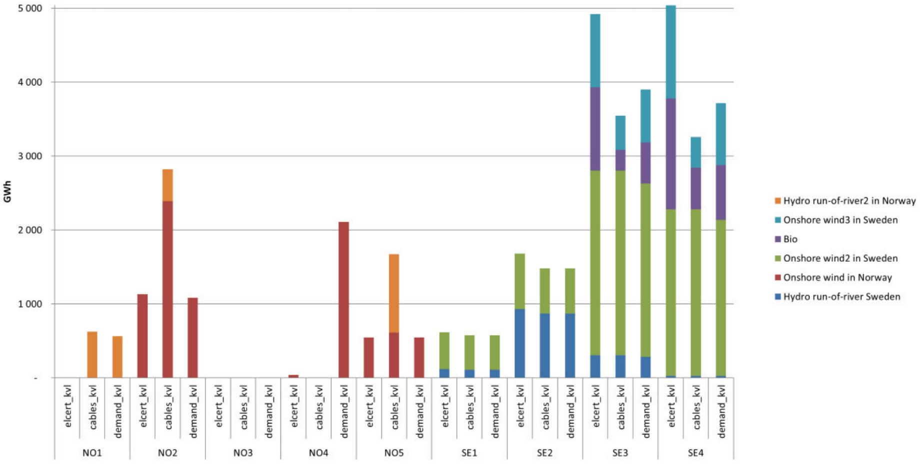

Figure 15 Green certificate generation by region and technology with Kirchhoff's voltage law imposed

When Kirchhoff's voltage law is imposed (Figure 15), fewer Norwegian projects are developed. The transmission network is not capable of transmitting wind power from the NO3 and NO4 regions in northern Norway. Instead more new generation projects in southern parts of Sweden are developed. In the *demand_kvl* scenario, some wind projects in NO4 become profitable.

The *cables_kvl* scenario triggers more expensive hydro run-of-river projects in the southern parts of Norway, closer to the North-European markets. There is a tradeoff between favorable location versus intrinsic project profitability. New cables in the AC-network enables investments in more expensive technologies closer to the European markets. Increased local demand dampens these effects.

When we impose Kirchhoff's voltage law on the AC-network, more expensive projects are built. This increase the deadweight losses for society. The TSO can make grid investments to remove bottlenecks in the grid. As we see, a more flexible grid enables improved utilization of natural resources, but comes at a cost of capital[9].

Figure 15 seems to indicate that cheaper generation is reduced at the same time as more expensive generation increases (see for example the cables scenario in SE4 where generation from bio is reduced but more expensive wind3 projects are still producing). The reason is the seasonal production within the year. Bio generation is fully exploited in every timeslice the wind production is used (see Figure 28 in the appendix for details).

Table 3 reports how the green certificate scheme leads to crowding out in our different scenarios. Fridolfsson and Tangerås (2013) conclude that crowding out may arise from the certificate scheme, whereby costly new generation replaces inexpensive old renewable generation. They refer to a survey revealing plans to reduce production by 1.5 TWh renewable electricity and investing in new plants amounting to 5.1 TWh, implying a crowding out of 30 per cent. In our scenarios, new generation is crowding out old thermal generation, ranging from 0% to 34%. We get significantly higher crowding out effects when we include the KVL restriction, since it makes the grid less flexible, and more expensive local generation is supplied. More than 50 % of the thermal production is based on renewables, so our results support the conclusion that crowding out of old renewable generation may arise from the certificate scheme.

Table 3 Crowding out of old thermal generation due to green certificate scheme

	Kirchhoff's Voltage Law not imposed		Kirchhoff's Voltage Law imposed	
Scenario	Reduced thermal generation [GWh]	Crowding out [%]	Reduced thermal generation [GWh]	Crowding out [%]
Elcert	2 171	8 %	8 954	34 %
Cables	148	1 %	5 610	21 %
Demand	67	0 %	1 381	5 %

We conclude this section by showing observed market prices of electricity and green certificates[10]. Figure 16 shows observed prices since before the common green certificate market

---

[9] Further grid expansions may also have additional environmental impacts, which we do not consider here.

[10] We show 3 years forward prices of electricity because these are less volatile than spot prices, making it easier to see the trend in the figure. Data sources are Thompson Reuters Datastream and SKM Svensk Kraftmäkling at http://www.skm.se/priceinfo/history.

was opened (green certificate prices in 2011 are from the national Swedish market that existed before the common market was established).

Figure 16 Observed prices of electricity (3 years forward) and green certificates

The results from our *elcert* scenarios do not seem unreasonable, based on these observations. Electricity prices have fallen considerably since the common Norwegian-Swedish green certificate market was established in 2012, and green certificate prices were of the same magnitude as electricity prices in 2016. Our analysis only considers the 26,4 TWh target decided in 2012. The Swedish expansions in 2015 and 2017 may of course have affected the observed certificate prices, as Figure 16 supports. New cables towards Northern Europe are planned to operate in 2019 and 2020, and should be expected to raise electricity prices, as our *cables* scenario indicate.

6 Conclusions

We have implemented a partial equilibrium complementarity model and calculated the theoretic value of green certificates from market equilibria in a representative production year assuming perfect competition and perfect market information.

To force a 10 per cent increase in electricity production by increased renewable generation in Norway and Sweden requires a green certificate price in the same range as the price of electricity.

It is costly for society to subsidize more expensive renewable generation if there is no corresponding demand that can utilize the increase. The yearly cost for society of the support scheme without any new demand is in the range of 300 million Euro, meaning that 35-40 per cent of the full scheme certificate value would disappear in deadweight losses. This burden is shared between consumers and existing producers. New cables towards Europe are important for the efficiency of the support scheme. Transmission investments provides market integration which diminish deadweight losses. A local demand increase makes the electricity more valuable and has a similar effect.

The introduction of the green certificate scheme ceteris paribus leads to losses for existing producers due to considerable electricity price declines. Consumers gain when the price declines, while new renewable producers are assured the necessary profits from the green certificates. New cables towards Europe affect the burden sharing between producers and consumers. Improved cross-country exchange is advantageous for existing producers, unless bottlenecks in the grid allows the TSO to profit from the price differences. A concomitant demand increase would create the best outcome, increasing net social welfare and prevent export of subsidized power. The TSO gains from increased production in all scenarios. New cables create higher revenues (which may finance the investment), while local increase in demand dampens the TSO profits.

Furthermore, we conclude that the supranational green certificate support scheme may have considerable local welfare transfer effects. The regional market outcomes depend crucially on the transmission grid. Electricity production must be connected to the grid, and our results indicate that the geographical location of the project is relevant.

Grid investments that remove bottlenecks can make decentralized projects with favorable costs feasible. This would decrease green certificate prices and reduce deadweight losses. The societal benefit from improved utilization of natural resources must be weighed against the societal cost of making the grid investments.

In order to capture these effects, Kirchhoff’s voltage law should not be overlooked. It makes the project location in the grid matter more, and affects which projects that are built. Projects with favorable locations but more expensive production technologies are chosen, and they demand higher certificate prices. This results in higher deadweight losses.

On the surface a green certificate policy scheme seems very flexible and easy to implement, and politicians can leave it to the market to decide the best implementation of the policy goal. In reality grid expansions are often necessary for new production and decisive for profitability. The TSO may strongly affect where new production will be profitable. This creates difficult planning and decision problems for the electricity generators. Infrastructure investments in the grid affect which projects are built, and as a consequence also the regional welfare effects from the tradable green certificate scheme. The net social welfare effects depend on the TSO's ability to optimize its grid investments.

7 Acknowledgements

This work was made possible by the financial support of the Norwegian Research Council through the funding of the project "Regional effects of energy policy" (216513), and by the financial support from Enova SF for the doctoral work of Per Ivar Helgesen.

The authors would like to thank Anna Krook-Riekkola, Pernille Seljom, Arne Lind, Bernhard Kvaal and Karl Ludvig Refsnæs for their valuable comments and suggestions. We also thank participants at the CenSES annual conference for valuable feedback on preliminary findings, and four anonymous reviewers for their constructive comments.

8 References

Amundsen ES, Bergman L. Integration of multiple national markets for electricity: The case of Norway and Sweden. Energy Policy 2007;35; 3383-3394.

Amundsen ES, Bergman L. Green Certificates and Market Power on the Nordic Power Market. Energy Journal 2012;33; 101-117.

Aune FR, Dalen HM, Hagem C. Implementing the EU renewable target through green certificate markets. Energy Econ. 2012;34; 992-1000.

Azevedo IML, Morgan MG, Lave L. Residential and Regional Electricity Consumption in the U.S. and EU: How Much Will Higher Prices Reduce CO2 Emissions? The Electricity Journal 2011;24; 21-29.

Bjorndal M, Jornsten K. Benefits from coordinating congestion management - The Nordic power market. Energy Policy 2007;35; 1978-1991.

Boomsma TK, Linnerud K. Market and policy risk under different renewable electricity support schemes. Energy 2015;89; 435-448.

Borenstein S, Bushnell J. An empirical analysis of the potential for market power in California's electricity industry. J. Indust. Econ. 1999;47; 285-323.

Borenstein S, Bushnell J, Kahn E, Stoft S. Market power in California electricity markets. Utilities Policy 1995;5; 219-236.

Bushnell J. A mixed complementarity model of hydrothermal electricity competition in the western United States. Oper. Res. 2003;51; 80-93.

Bushnell JB, Mansur ET, Saravia C. Vertical arrangements, market structure, and competition: An analysis of restructured US electricity markets. Am. Econ. Rev. 2008;98; 237-266.

Bussieck M, Meeraus A, 2004. General Algebraic Modeling System (GAMS), In: Kallrath J (Ed), Modeling Languages in Mathematical Optimization. Springer US; 2004. pp. 137-157.

Butler L, Neuhoff K. Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. Renew. Energy 2008;33; 1854-1867.

Bye T, Hope E. Deregulering av elektrisitetsmarkedet: Norske erfaringer (Deregulation of the electricity market: Norwegian experiences). Økonomisk forum 2007;61; 17-25.

Böhringer C, Hoffmann T, Rutherford TF. Alternative Strategies for Promoting Renewable Energy in EU Electricity Markets. Applied Economics Quarterly 2007;53; 9-30.

Coulon M, Khazaei J, Powell WB. SMART-SREC: A stochastic model of the New Jersey solar renewable energy certificate market. Journal of Environmental Economics and Management 2015;73; 13-31.

Couture TD, Jacobs D, Rickerson W, Healey V, 2015. The Next Generation of Renewable Electricity Policy, NREL Technical Report. National Renewable Energy Laboratory p. 36.

Currier KM, Sun Y. Market Power and Welfare in Electricity Markets Employing Tradable Green Certificate Systems. International Advances in Economic Research 2014;20; 129-138.

Dahlan NY, Kirschen DS. An Empirical Approach of Modelling Electricity Prices in an Oligopoly Market. 2012 IEEE International Conference on Power and Energy (Pecon) 2012; 256-261.

Dirkse SP, Ferris MC. The path solver: a nommonotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software 1995;5; 123-156.

El Kasmioui O, Verbruggen A, Ceulemans R. The 2013 reforms of the Flemish renewable electricity support: Missed opportunities. Renew. Energy 2015;83; 905-917.

ENTSO-E, 2014. Maximum NTC values. ENTSO-E Nordic Group.

EU, 2009. EU Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, in: Parliament E (Ed.), Official Journal of the European Union, L 140, 05 June 2009, pp. 16-62.

Fridolfsson S-O, Tangerås TP. A reexamination of renewable electricity policy in Sweden. Energy Policy 2013;58; 57-63.

Gebrekiros Y, Doorman G, Jaehnert S, Farahmand H. Reserve procurement and transmission capacity reservation in the Northern European power market. Int. J. Electr. Power Energy Syst. 2015;67; 546-559.

Haas R, Resch G, Panzer C, Busch S, Ragwitz M, Held A. Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources - Lessons from EU countries. Energy 2011;36; 2186-2193.

Held A, Ragwitz M, Gephart M, de Visser E, Klessmann C, 2014. Design features of support schemes for renewable electricity. Ecofys.

Helgesen PI, Tomasgard A. An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's Laws and Nash-Cournot competition. Energy Econ. 2018;70; 270-288.

Hjalmarsson E, 2000. Nord Pool: A Power Market Without Market Power, Working Papers in Economics no 28, University of Gothenburg, p. 39.

Hobbs BF. Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. Ieee Transactions on Power Systems 2001;16; 194-202.

Hobbs BF, Drayton G, Fisher EB, Lise W. Improved transmission representations in oligopolistic market models: Quadratic losses, phase shifters, and DC lines. Ieee Transactions on Power Systems 2008;23; 1018-1029.

Holstad M, Pettersen FEL. How does electricity consumption react to price changes? (In Norwegian). Economic Analyses (Økonomiske analyser) 2011.

IEA, 2014a. Energy Technology Perspectives 2014. OECD/International Energy Agency, Paris.

IEA, 2014b. World Energy Outlook 2014. OECD/International Energy Agency, Paris.

IEA, 2017. Energy Technology Perspectives 2017. OECD/International Energy Agency, Paris.

IFE/NVE, 2014. Times Norway Nr 90 database, Institute for Energy Technology.

Jaraite J, Kazukauskas A. The profitability of electricity generating firms and policies promoting renewable energy. Energy Econ. 2013;40; 858-865.

Johnsen TA, 1998. Modelling the Norwegian and Nordic Electricity Markets, Department of Economics. University of Oslo, Oslo.

Kildegaard A. Green certificate markets, the risk of over-investment, and the role of long-term contracts. Energy Policy 2008;36; 3413-3421.

Limpaitoon T, Chen Y, Oren SS. The Impact of Carbon Cap and Trade Regulation on Congested Electricity Market Equilibrium. J. Regul. Econ. 2011;40; 237-260.

Limpaitoon T, Chen Y, Oren SS. The Impact of Imperfect Competition in Emission Permits Trading on Oligopolistic Electricity Markets. Energy Journal 2014;35; 145-166.

Liski M, Vehviläinen I, 2016. Gone with the Wind? An Empirical Analysis of the Renewable Energy Rent Transfer, in: Aichele R, Fuest C (Eds.), CESifo Working Paper Series. CESifo, Munich, Germany.

Makkonen M, Nilsson M, Viljainen S. All quiet on the western front? Transmission capacity development in the Nordic electricity market. Economics of Energy & Environmental Policy 2015;4; 161-176.

Menanteau P, Finon D, Lamy M-L. Prices versus quantities: choosing policies for promoting the development of renewable energy. Energy Policy 2003;31; 799-812.

Mirza FM, Bergland O. Market Power in the Norwegian Electricity Market: Are the Transmission Bottlenecks Truly Exogenous? Energy Journal 2015;36; 313-330.

Morthorst PE. The development of a green certificate market. Energy Policy 2000;28; 1085-1094.

MPE, 2011. Agreement between the Government of the Kingdom of Norway and the Government of the Kingdom of Sweden on a common market for electricity certificates, Ministry of Petroleum and Energy, p. 10.

MPE, 2012. Electricity certificates, Ministry of Petroleum and Energy.

Munoz FD, Sauma EE, Hobbs BF. Approximations in power transmission planning: implications for the cost and performance of renewable portfolio standards. J. Regul. Econ. 2013;43; 305-338.

Neuhoff K, 2003. Integrating Transmission and Energy Markets Mitigates Market Power, DAE Working Paper Series. University of Cambridge.

Nilsson M, Sundqvist T. Using the market at a cost: How the introduction of green certificates in Sweden led to market inefficiencies. Utilities Policy 2007;15; 49-59.

Nohlgren I, Svärd SH, Jansson M, Rodin J, 2014. El från nya och framtida anläggningar 2014, Elforsk rapport. Elforsk, p. 234.

Oggioni G, Smeers Y, Allevi E, Schaible S. A Generalized Nash Equilibrium Model of Market Coupling in the European Power System. Netw Spat. Econ. 2012;12; 503-560.

Papavasiliou A, Chen YH, Oren SS, Ieee, 2009. Environmental Regulation in Transmission-Constrained Electricity Markets, 2009 Ieee Power & Energy Society General Meeting, Vols 1-8. Ieee, New York; 2009. pp. 2110-+.

Pérez de Arce M, Sauma E. Comparison of Incentive Policies for Renewable Energy in an Oligopolistic Market with Price-Responsive Demand. 2016;37; 159-198.

Qi R, 1997. Generalized spatial price equilibria with semicontinuous market structures. University of Pennsylvania, Ann Arbor, pp. 105-105 p.

REN21, 2015. Renewables 2015 Global Status Report, in: Sawin JL (Ed.). REN21, Paris: REN21 Secretariat, p. 251.

Rosnes O. Subsidies for renewable energy in inflexible power markets. J. Regul. Econ. 2014;46; 318-343.

Schweppe FC, Caramanis MC, Tabors RD, Bohn RE. Spot pricing of Electricity. Springer US; 1988.

Sidelnikova M, Weir DE, Groth LH, Nybakke K, Stensby KE, Langseth B, Fonneløp J, Isachsen O, Haukeli I, Paulen S, Magnussen I, Husabø LI, Ericson T, Qureishy TH, 2015. Kostnader i energisektoren. Norwegain Water Resources and Energy Directorate, p. 238.

Tangeras TP. Renewable Electricity Policy and Market Integration. Energy Journal 2015;36; 331-353.

9 Appendix

9.1 The mathematical model

For definition of sets, parameters and variables, see section 3.

Producer problem (perfect competition)

The producer chooses his generation and sales in order to maximize profit. He acts as a price taker, and assumes that his production will not influence the market price (perfect competition). Producer *f* solves the following problem:

$$\underset{s_{frt},\, x_{ift}}{Max} \qquad \textstyle\sum_{r \in R} \sum_{t \in T} \left[(p_{rt} - w_{rt}) s_{frt} - \sum_{i \in I} (c_i - w_{rt}) x_{ift} + \sum_{i \in I_c} \mu \, x_{ift} \right]$$

Each producer maximizes his profit, which is comprised by three components: income, production cost and certificate income. The wheeling cost w_r is paid to the TSO for transporting power s_{frt} to region r from the transmission network. When the producer generates power x_{ift} in its own region, the TSO pays the regional wheeling fee to the producer for receiving power into the network. The producer also receives the certificate price μ for each MWh of renewable electricity x_{ift} generated using a technology eligible for certificates $i \in I_c$.

$$Supply: \qquad \sum_{r \in R} s_{frt} - \sum_{i \in I} x_{ift} \leq 0 \qquad , f \in F, t \in T \qquad (\omega_{ft})$$

The supply constraint inhibits the producer from selling more power s_{frt} than he produces x_{ift} in each timeslice. It is possible to produce more power than supplied. This would imply that the marginal income ω_{ft} is zero.

$$Flexlim: \qquad x_{ift} \leq G_{if} \frac{h_t}{H} f_i \qquad , i \in I, f \in F, r \in R \qquad (\varphi_{ift})$$

The Flexlim constraint represents flexible production limits. We assume that each production technology has an upper capacity bound G_{if} in the analysis period. If the flexibility parameter f_i is greater than one, then technology i has timing flexibility to move production between timeslices - else production capacity is assumed to be constant, thus the production limit is proportional to the length of the timeslice. The flexible production limit has a shadow price of φ_{ift}.

$$Prodlim: \qquad \sum_{t} x_{ift} \leq G_{if} \qquad , i \in I, f \in F \qquad (\psi_{if})$$

The Prodlim constraint represents the total production limits. If technology i has timing flexibility, it still must produce within the capacity bound G_{if} in the analysis period. The production limit has a shadow price of ψ_{if}.

At last we add nonnegativity constraints on the decision variables for supply and generation.

$$s_{frt} \geq 0, x_{ift} \geq 0$$

The Karush-Kuhn-Tucker (KKT) conditions are found by formulating the Lagrangian function and taking partial derivatives with respect to the independent variables and to the Lagrange-multipliers (dual variables).

Grid owner / TSO problem (Nash-Bertrand assumption)

We assume that the grid owner naively acts as a price taker, and chooses grid flows to maximize her profit while adhering to Kirchhoff's current and voltage laws and transmission capacities. Since we assume perfect competition, arbitrage opportunities will not occur, and we do not consider arbitrage in this model.

$$\underset{z_{rkt}}{Max} \quad \sum_{r\in R}\sum_{t\in T}\left[w_{rt}\left(\sum_{f\in F} s_{frt} - \sum_{i\in I, f\in F_r} x_{ift}\right)\right]$$

The grid owner maximizes his income from the wheeling fee on power flowing to each region.

$$KCL: \quad \sum_{f\in F} s_{frt} - \sum_{f\in F_r}\sum_{i\in I} x_{ift} - \sum_{k\in R} z_{krt} + \sum_{k\in R} z_{rkt} = 0 \qquad , r \in R, t \in T \qquad (w_{rt})$$

The KCL constraint states Kirchhoff's current law: The sum of currents flowing into a node or region is equal to the sum of currents flowing out of that node, so the sum of all currents meeting in region *r* must be zero. The shadow price w_{rt}equals the cost of transporting electricity from the grid to region *r* in timeslice *t*.

$$KVL: \quad \sum_{(r,k)\in K_v} R_{rk}(z_{krt} - z_{rkt}) = 0 \qquad , v \in N, t \in T \qquad (\kappa_{vt})$$

Kirchhoff's voltage law (also called Kirchhoff's loop rule) is represented by the KVL constraint. The law says that the directed sum of the electrical potential differences (voltages) around any closed cycle in the network is zero. A potential difference over the cycle would create a current, and we cannot have a positive flow running through any cycle in the network. The sum of flows adjusted by the reactance R_{rk} of the line between region *r* and region *k* must be zero.

$$Flowlim: \quad z_{rkt} \le L_{rk} h_t \qquad , (r,k) \in K, t \in T \qquad (\tau_{rkt})$$

The flowlim constraint represents the capacity of the lines. This capacity depends on temperature, security limits and other parameters, but we assume a directed net transfer capacity L_{rk} for each line. We assumed the line capacity to be constant, thus the flow limit is proportional to the length of the timeslice.

We also need nonnegativity constraints on the directed flow variables.

$$z_{rkt} \ge 0$$

Consumer / Market clearing

The representative consumer acts as a price taker. We assume an iso-elastic demand curve. Demand in a region *r* during timeslice *t* is $Q_{rt} = Q_{0rt}\left(\frac{(p_{rt}+t_{\mu})}{P_{0rt}}\right)^{-\sigma}$, where σ is the absolute value of the own-price demand elasticity. Her willingness to pay for a quantity q_{rt} is $W_{rt}(q_{rt}) = P_{0rt}\left(\frac{q_{rt}}{Q_{0rt}}\right)^{-\frac{1}{\sigma}}$, where $q_{rt} = \sum_f s_{frt}$. The consumer wants to maximize her consumer surplus:

$$\underset{Q_{rt}^{*}}{Max}\sum_{t\in T}\left[\int_0^{Q_{rt}^{*}}\left(W_{rt}(q_{rt}) - p_{rt} - t_{\mu}\right)dq_{rt}\right] \quad \text{where} \quad W_{rt}(q_{rt}) = P_{0rt}\left(\frac{q_{rt}}{Q_{0rt}}\right)^{-\frac{1}{\sigma}}$$

The KKT conditions give us the Market Clearing Conditions

$$P_{0rt}\left(\frac{\sum_{f\in F} s_{frt}}{Q_{0rt}}\right)^{-\frac{1}{\sigma}} - p_{rt} - t_{\mu} = 0 \qquad , r\in R, t\in T \quad (\,p_{rt}\ \text{free})$$

Tax agent

The tax agent minimizes the tax needed to finance the green certificates that are necessary to fulfill the renewable quota obligation.

$$\underset{t_{\mu}}{\text{Min}}\, t_{\mu}$$

The tax rate should be as low as possible, in order to minimize the socioeconomic deadweight loss the tax will incur. The tax on electricity must cover the value of the certificates.

$$Tax\!: \qquad \sum_{t\in T}\sum_{r\in R}\sum_{f\in F} s_{frt}\, t_{\mu} \geq \sum_{t\in T}\sum_{f\in F}\sum_{i\in I_c} x_{ift}\mu \qquad (\lambda_1)$$

The tax rate is nonnegative.

$$t_{\mu} \geq 0 \qquad (\lambda_2)$$

Certificate/quota constraint

Regulating authorities decide a volume *V* of new renewable electricity production.

$$Elcert\!: \qquad \sum_{i\in I_c}\sum_{f\in F}\sum_{t\in T} x_{ift} \geq V \qquad \perp (\mu \geq 0)$$

The dual price μ of this constraint becomes the value of certificates. This is the lowest certificate value needed to achieve the target of renewable production. Producers could choose to generate more than the target, in which case the certificate value will become zero.

9.2 Formulas for LRMC and LCOE

The Long-Run Marginal Cost (LRMC) in Table 2 is calculated as

$$LRMC_i = I_i \frac{r}{(1-(1+r)^{-T_i})} + \frac{F_i}{365 \cdot 24 \cdot a_i} + SRMC_i \tag{13}$$

The Levelized Cost of Electricity (LCOE) is calculated as

$$LCOE_i = SRMC_i + (LRMC_i - SRMC_i)\frac{(1-(1+r)^{-T_i})}{(1-(1+r)^{-E})} \tag{14}$$

where E is the lifetime of green certificates, which is 15 years in the Swedish-Norwegian support scheme.

9.3 Demand drivers, market factors and timeslices

Consumption and production in Norway and Sweden may differ substantially from year to year, depending on temperature and the hydrological balance. 2012 was cold, while 2013 was a dry year with precipitation below normal for Scandinavia. This resulted in higher electricity prices, see Figure 17. 2014 was a warm year, with lower electricity prices.

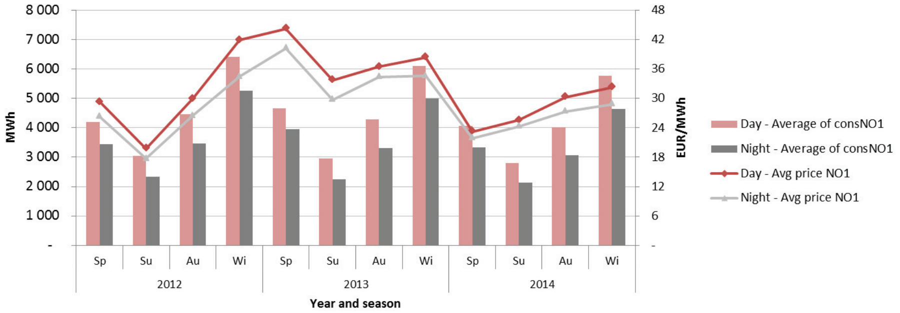

Figure 17 Average electricity price and consumption in East Norway (NO1) by year and season. Source: NordPoolSpot

These effects make market prices and demand appear positively correlated. Consumption is higher during winter hours than in summer hours, and there is a tendency that prices are higher when consumption is high (the correlation coefficient between price and volume is 0,45). We define timeslices to include this seasonal variation.

Figure 18 shows average hourly consumption volumes and prices for each price area in Norway and Sweden based on hourly observations from 2012-2014. We notice that consumption seems relatively independent of the price, indicating inelastic demand.

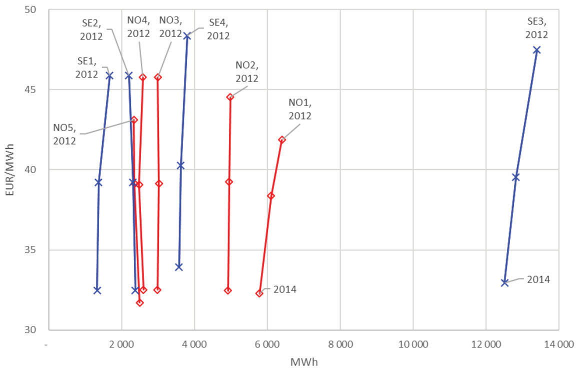

Figure 18: Electricity consumption and price, winter day averages, 2012-2014. Source: NordPoolSpot

Both prices and consumption volumes are highest in 2012 and lowest in 2014. Outdoor temperature is an important demand driver, since electricity is commonly used for space and water heating. Figure 19 shows heating degree days (with base 17 degrees Celsius), indicating that 2012 was a cold year and 2014 a warm year.

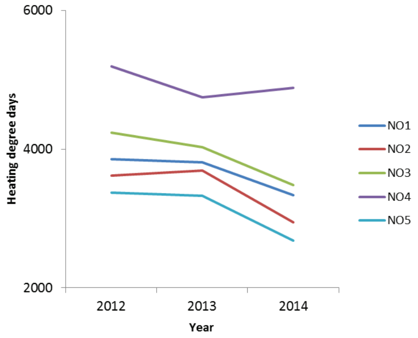

Figure 19 Heating degree days. Source: Norwegian Meteorological Institute

9.3.1 Day versus night

European electricity prices are low during night. Since Norway and Sweden have flexible production due to high shares of controllable hydro power, it is profitable to import during night and export during day. All the cross-border connections show a similar pattern over the day, except the relatively small northern connectors from Norway towards Russia and Finland.

Figure 20 shows average net flow into Norway and Sweden by season and hour of the day.

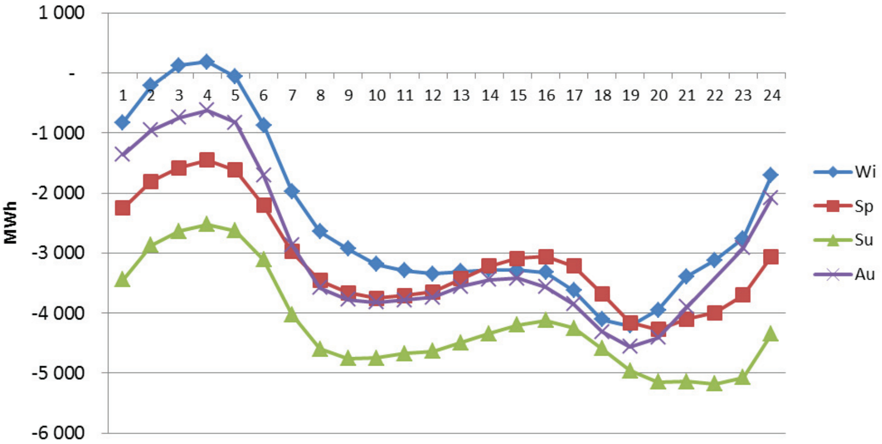

Figure 20 Average net power flow into Norway and Sweden by season and hour of day, 2012-2014. Source: NordPoolSpot

Flows during hours 23-24 and 06-07 are similar to afternoon hours during spring and summer, while flows during hours 00-06 are significantly higher than the rest of the day. Based on Figure 20, we define night-time as the six hours from 00-06, and daytime as the 18 hours from 07-24.

9.3.2 Seasonal variation

Figure 21 shows the flow pattern of electricity into Norway and Sweden by sequential day of the year. We notice that the average net flow goes out from Norway and Sweden during the year, as both countries are net exporters. During 2012-2014 there have been large export days during the whole year, while there are summer days without net import during this period. There are apparent changes during the year, as the calendar seasons have different characteristics (see also Figure 4). Norway and Sweden have relatively big temperature differences between summer and winter, which affects electricity consumption significantly as electricity is used for heating especially in Norwegian residents. The spring is characterized by much run-of-river hydro production, compared to the autumn.

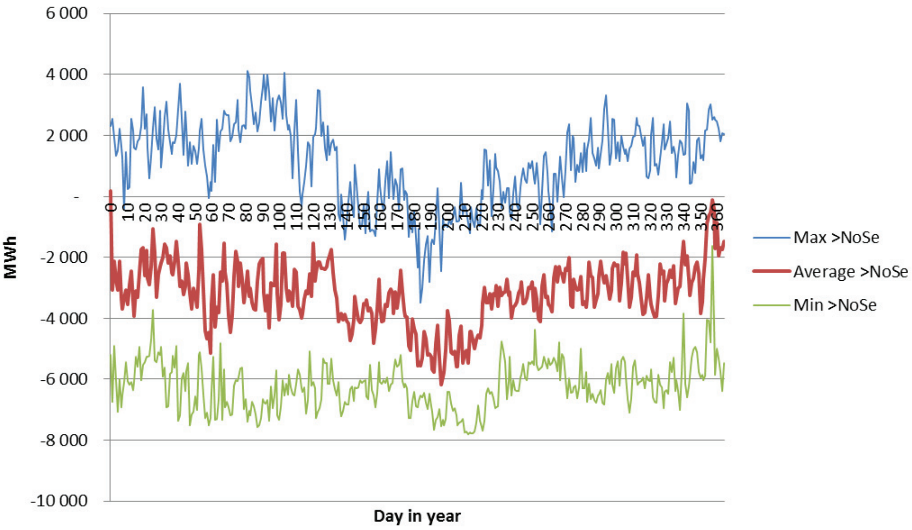

Figure 21 Electricity flow into Norway and Sweden by day, 2012-2014. Source: NordPoolSpot

We could try to improve the timeslice definitions by finding date limits that provides maximum discrimination between seasons, but it is hard to find such dates based on Figure 21. Separate area connections may have date candidates which divide seasons more clearly, but these dates shift from connection to connection. For the total system we conclude that calendar seasons winter, spring, summer and autumn explain a significant share of the yearly variation.

9.3.3 Weekday variation

The consumption, production and flow of electricity change during the week. Most shops are closed on Sundays, and many business sectors have low activity during weekends. The electricity demand decreases as a result. Flexible hydro power producers can store water for later production, while inflexible and intermittent supply technologies remain producing electricity and earn lower power prices. (Some technologies may earn subsidies like green certificates or feed-in-tariffs in addition to the market price of electricity, and wish to produce with very low or even negative market prices.)

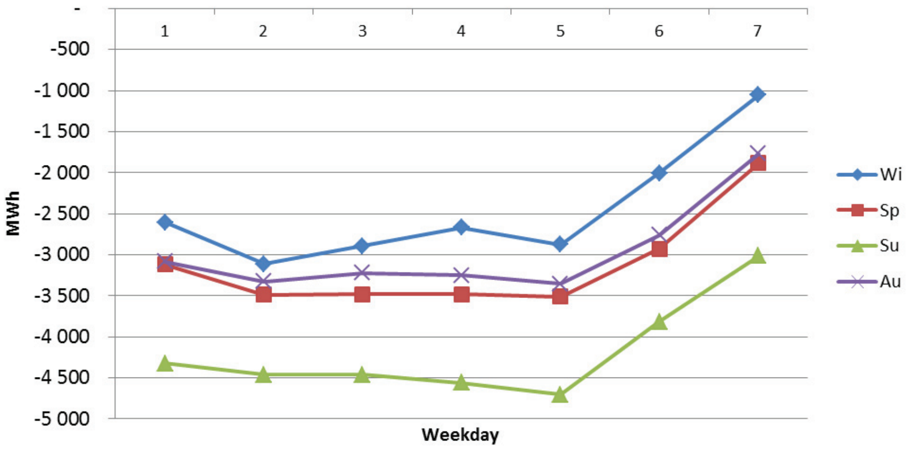

Figure 22 Average flow of electricity into Norway and Sweden by weekday and season, 2012-2014. Source: NordPoolSpot

Figure 22 shows that there is a weekend effect on power flow into Norway and Sweden. In this study we ignore this effect.

9.4 Technology capacities

Capacities of available technologies per area are presented in Table 4.

Table 4 Capacities of available technologies per area

		NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4
		[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]	[GWh/year]
Existing	HYDREG0	23 854	34 657	12 360	16 435	13 954	16 574	17 602	3 257	252
	HYDROR0	6 772	9 840	3 509	4 666	3 962	2 765	21 721	7 128	702
	THERMAL0	783	1 138	406	540	458	1 170	2 566	8 222	3 608
	WIND0	-	288	808	400	73	594	988	2 851	2 531
	NUCLEAR0	-	-	-	-	-	-	-	62 239	-
Fossil	NG01	300	300	300	300	300	300	300	300	300
	NGCC	300	300	300	300	300	300	300	300	300
	NG02CO2	300	300	300	300	300	300	300	300	300
	NGPEAK_101	300	300	300	300	300	300	300	300	300
New hydro	HYDRUN04	446	306	205	287	755	-	-	-	-
	HYDRUN05	669	460	308	431	1 133	-	-	-	-
	HYDREG07	892	613	410	575	1 510	-	-	-	-
	HYDREG_101	-	-	-	-	-	710	754	140	11
	HYDRUN_101	-	-	-	-	-	118	931	305	30
	BIO	-	-	-	-	-	500	1 000	1 500	2 000
wind	WIND_on1SE	-	-	-	-	-	200	300	1 000	900
	WIND_on2SE	-	-	-	-	-	400	600	2 000	1 800
	WIND_on3SE	-	-	-	-	-	800	1 200	4 000	3 600
	WIND_offSE	-	-	-	-	-	800	1 200	4 000	3 600
	WIND_offNO	-	300	300	300	300	-	-	-	-
wind projects	W1A107N2	-	34	-	-	-	-	-	-	-
	W2A128N3	-	-	165	-	-	-	-	-	-
	W3A112N4	-	-	-	368	-	-	-	-	-
	W4A111N5	-	-	-	-	25	-	-	-	-
	W5A108N2	-	23	-	-	-	-	-	-	-
	…	…	…	…	…	…	…	…	…	…

9.5 Transmission network

Transmission values for the transmission network are presented in Table 5. Six transmission line capacities were adjusted in relevant scenarios.

Table 5 Network capacities based on ENTSO-E maximum net transfer capacities

From	To	Capacity [MW]	Reactance
NO2	DK1	1000 / 1632	(n.a.)
DK1	NO2	1000 / 1632	(n.a.)
NO2	DEU	0 / 1400	(n.a.)
DEU	NO2	0 / 1400	(n.a.)
NO2	GBR	0 / 1400	(n.a.)
GBR	NO2	0 / 1400	(n.a.)
NO1	NO2	2200	2
NO1	NO3	500	2
NO1	NO5	300	2
NO1	SE3	2145	2
NO2	NO1	3500	2
NO2	NO5	500	2
NO3	NO1	500	2
NO3	NO4	200	2
NO3	SE2	600	2
NO4	NO3	1000	2
NO4	SE1	700	2
NO4	SE2	250	2
NO5	NO1	3700	2
NO5	NO2	600	2
SE1	NO4	600	2
SE1	SE2	3300	1.5
SE2	NO3	1000	2
SE2	NO4	300	2
SE2	SE1	3300	2
SE2	SE3	7300	1.5
SE3	NO1	2095	2
SE3	SE2	7300	2
SE3	SE4	5300	2
SE4	SE3	2000	2
NO2	NLD	700	(n.a.)
NO4	FIN	70	2
SE1	FIN	1500	2
SE3	DK1	680	2
SE3	FIN	1200	2
SE4	DEU	615	2
SE4	DK2	1300	2
SE4	POL	600	2
DEU	SE4	615	(n.a.)
NLD	NO2	700	(n.a.)
DK1	SE3	740	(n.a.)
DK2	SE4	1700	2
POL	SE4	600	(n.a.)
RUS	NO4	56	(n.a.)
FIN	NO4	70	2
FIN	SE1	1100	2

FIN	SE3	1200	(n.a.)

9.6 Reference demands and reference prices

Table 6 shows reference demands and reference prices in each area and timeslice.

Table 6 Reference demands (Q_0) and reference prices (P_0) per area and timeslice

	Autumn Day		Autumn Night		Spring Day		Spring Night		Summer Day		Summer Night		Winter Day		Winter Night	
	Q_0	P_0	Q_0	P_0	Q_0	P_0	Q_0	P_0	Q_0	P_0	Q_0	P_0	Q_0	P_0	Q_0	P_0
Area	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]	[GWh]	[EUR/MWh]
NO1	6 965	32.2	1 788	29.4	7 123	32.2	1 975	29.5	4 844	26.3	1 233	23.9	9 870	37.5	2 684	32.6
NO2	6 453	32.3	1 826	29.4	6 711	32.4	1 990	29.5	5 344	26.2	1 552	23.7	8 023	38.8	2 305	32.7
NO3	4 211	36.9	1 223	31.6	4 145	35.3	1 245	30.1	3 473	30.4	1 025	25.1	4 862	39.1	1 420	32.3
NO4	3 511	36.4	1 046	31.6	3 505	34.7	1 079	30.1	2 837	30.1	856	25.1	4 138	39.1	1 236	32.3
NO5	3 167	32.0	924	29.1	3 309	32.4	996	29.6	2 593	26.0	769	23.6	3 884	38.0	1 139	32.7
SE1	1 987	37.1	541	30.2	2 012	35.1	580	29.3	1 773	31.6	502	25.1	2 365	39.2	657	32.2
SE2	3 004	37.1	881	30.2	3 058	35.2	912	29.3	2 502	31.6	715	25.1	3 719	39.2	1 101	32.2
SE3	16 656	37.6	4 387	30.2	17 221	35.3	4 837	29.3	13 517	32.0	3 579	25.1	20 895	40.0	5 715	32.2
SE4	4 671	38.1	1 168	30.2	4 865	36.2	1 321	29.3	3 895	34.4	972	25.2	5 936	40.9	1 573	32.2
DEU		48.6		26.9		43.7		28.3		43.2		27.8		48.8		24.4
DK1		38.7		27.4		36.6		27.7		39.0		25.4		38.7		25.4
DK2		41.1		29.0		37.7		28.0		38.2		25.9		40.9		26.6
FIN		42.7		31.3		39.0		30.5		37.3		25.4		43.4		32.8
GBR		64.0		42.7		61.7		44.9		56.9		40.4		62.0		43.0
NLD		55.3		35.4		53.1		36.6		49.7		32.7		56.2		35.6
POL		49.4		30.4		43.7		30.8		46.5		32.2		45.2		29.8
RUS		25.0		25.0		25.0		25.0		25.0		25.0		25.0		25.0

9.7 Other parameters

Production flexibility for regulable hydro technologies: $f_{hydreg0}$ =4, $f_{hydreg07}$ =4, f_{hydreg_101} =4.
Transport cost b = 0.1 [EUR/MWh]

9.8 Results

Table 7 shows numerical results from all scenarios.

Table 7 Numerical results from all scenarios

Scenario	No Kirchhoff voltage law	Kirchhoffs voltage law imposed	[unit]
Base	Avg electr. price = 32.87 Total supply = 288 Net exports = 25.1	Avg electr. price = 30.32 Total supply = 285 Net exports = 21.2	[EUR/MWh] [TWh] [TWh]
Elcert (new elcert production earns certificates)	Avg electr. price = 27.99 Elcert price = 31.96 Elcert tax = 3.19 Total supply = 312 Net exports = 47.6 ΔConsumer surplus = +0.62 ΔOld suppliers = -1.62 (-17%) New suppliers = +0.42 ΔTSO profit = +0.28 Social Welfare chg = -0.30 Certificates value = 0.84 Deadweight loss = 36%	Avg electr. price = 26.52 Elcert price = 32.41 Elcert tax = 3.23 Total supply = 303 Net exports = 37.8 ΔConsumer surplus = +0.27 ΔOld suppliers = -1.19 (-13%) New suppliers = +0.40 ΔTSO profit = +0.15 Social Welfare chg = -0.37 Certificates value = 0.86 Deadweight loss = 43%	[EUR/MWh] [EUR/MWh] [EUR/MWh] [TWh] [TWh] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [percentage]
Cables (elcert production and increased integration from new cables)	Avg electr. price = 32.21 Elcert price = 26.56 Elcert tax = 2.68 Total supply = 314 Net exports = 52.7 ΔConsumer surplus = -0.50 ΔOld suppliers = -0.21 (-2%) New suppliers = +0.40 ΔTSO profit = +0.40 Social Welfare chg = 0.09 Certificates value = 0.70 Deadweight loss = (n.a.)	Avg electr. price = 26.44 Elcert price = 31.96 Elcert tax = 3.18 Total supply = 306 Net exports = 41.0 ΔConsumer surplus = +0.21 ΔOld suppliers = -1.14 (-13%) New suppliers = +0.40 ΔTSO profit = +0.49 Social Welfare chg = -0.04 Certificates value = 0.84 Deadweight loss = 5%	[EUR/MWh] [EUR/MWh] [EUR/MWh] [TWh] [TWh] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [percentage]
Demand (elcert production, new cables and demand increase by 10% in Norway and Sweden)	Avg electr. price = 33.73 Elcert price = 24.97 Elcert tax = 2.30 Total supply = 314 Net exports = 27.7 ΔConsumer surplus = +0.67 ΔOld suppliers = +0.30 (+3%) New suppliers = +0.41 ΔTSO profit = +0.33 Social Welfare chg = 1.70 Certificates value = 0.66 Deadweight loss = (n.a.)	Avg electr. price = 31.68 Elcert price = 25.92 Elcert tax = 2.38 Total supply = 310 Net exports = 22.8 ΔConsumer surplus = +0.53 ΔOld suppliers = +0.46 (+5%) New suppliers = +0.38 ΔTSO profit = +0.27 Social Welfare chg = 1.64 Certificates value = 0.68 Deadweight loss = (n.a.)	[EUR/MWh] [EUR/MWh] [EUR/MWh] [TWh] [TWh] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [Bill EUR] [percentage]

In Figure 23 we break down the welfare redistribution effects for each price area in the *elcert* scenario without considering Kirchhoff's Voltage Law. We also include the TSO's profit change.

Figure 23 Geographical welfare redistribution effects comparing base and *elcert* scenario without considering Kirchhoff's Voltage Law

Figure 23 shows that existing producers lose and consumers gain, but we notice that the redistribution of welfare is different from area to area. In total we see that there are more negative than positive changes, indicating a deadweight loss for the scheme. Two regions have a positive aggregated welfare effect (NO5 and SE4), thanks to localization of new production facilities. In this scenario some of the old production is replaced by new certificate production (crowding out). This leads to big profit losses in affected areas (production from old suppliers is reduced by 2.5 TWh in SE3). We notice that the TSO profit increases, due to increased power flows.

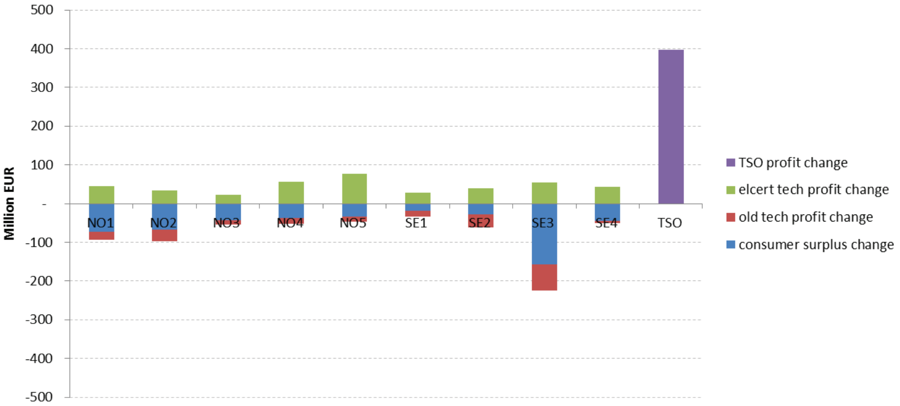

Figure 24 Geographical welfare redistribution effects comparing base and *cables* scenario (green certificate scheme and new cables towards Europe) without considering Kirchhoff's Voltage Law

The cables scenario reveals a different picture in Figure 24. Price changes are small in this scenario, so the welfare distribution changes are much smaller. Both consumers and old suppliers lose, in order to provide income to new suppliers. SE3 is the area with the by far highest electricity consumption, and the negative change in consumer surplus is only proportional to the use. NO4 and NO5 are the only regions with an increase in total welfare. The TSO profits from increased power flows, where Norway and Sweden are exporting high volumes towards Northern Europe. All in all this turns out as a rather balanced solution, with a small deadweight loss. Welfare is transferred from consumers and old suppliers to new suppliers and the TSO, and Europe is consuming the renewable electricity.

The solution to the demand scenario in Figure 25 shows yet another regional distribution. NO4, NO5 and SE2 are areas which increase their welfare in this scenario, while SE1 is in balance. Consumers bear the heaviest burdens in this scenario, and these are the four areas with the lowest consumption. High consumption areas suffer the biggest welfare losses in this scenario.

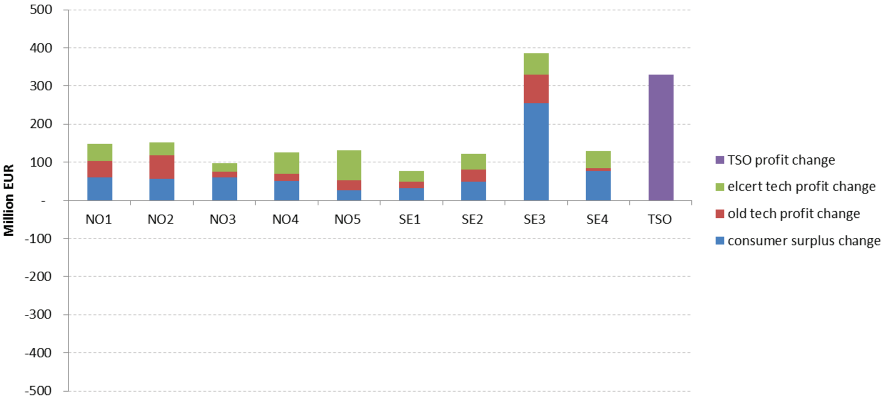

Figure 25 Geographical welfare redistribution effects comparing base and *demand* scenario (green certificate scheme with new cables and increased demand in Norway and Sweden) without considering Kirchhoff's Voltage Law

The geographical welfare distribution effects in the *elcert_kvl* scenario (with Kirchhoff's voltage law imposed) is presented in Figure 26. This scenario has considerable welfare transfers from existing suppliers to consumers in most areas, but not in NO1, NO2 and NO5. Electricity prices decrease in all price areas, but the green certificate tax makes consumers suffer from higher prices in East, South and West Norway. Only NO5 and SE4 have a positive net welfare effect in this scenario.

Figure 26 Geographical welfare redistribution effects going from base case to elcert scenario with Kirchhoff's Voltage Law imposed (*elcert_kvl* scenario)

In the *demand_kvl* scenario old producers profit increase due to higher prices. Higher prices make consumers lose, but consumer surplus increase in most areas due to the positive shift in the demand curve. Consumers in NO1, NO2 and NO5 lose (see Figure 27).

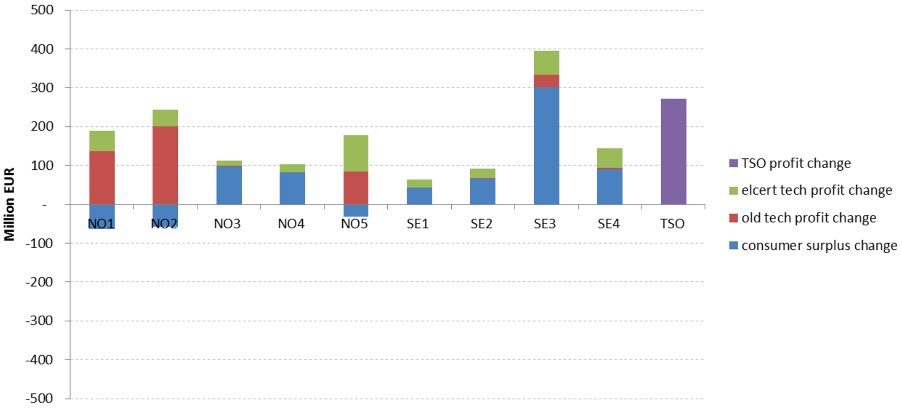

Figure 27 Geographical welfare distribution effects going from base case to elcert scheme with new cables and increased demand in Norway and Sweden with Kirchhoff's Voltage Law imposed (*demand_kvl* scenario)

Figure 28 shows selected technologies eligible for green certificates in SE3 and SE4, detailing certain aspects of Figure 15.

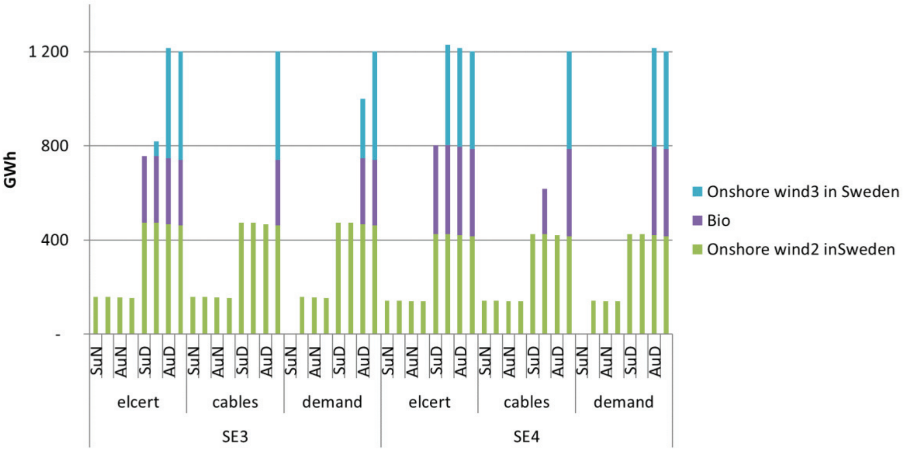

Figure 28 Certificate generation by region with Kirchhoff's Voltage Law imposed.

The figure shows that bio production is fully exploited in every time period when the more expensive wind production is used. Figure 28 also shows some small variations in production between time periods. There are two reasons for this:

1) Time periods have slightly different numbers of hours, resulting in different production quantities
2) Regulable hydro is shifted between periods and affect production levels in such timeslices.

Paper III

Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport

Paper III

Energy 156 (2018) 196–212

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport

Per Ivar Helgesen [a], *, Arne Lind [b], Olga Ivanova [c], Asgeir Tomasgard [a]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Norway
[b] Department of Energy Systems, Institute for Energy Technology, Norway
[c] Department of Urbanisation, Traffic and Transport, PBL Netherlands Environmental Assessment Agency, The Netherlands

ARTICLE INFO

Article history:
Received 7 May 2017
Received in revised form
14 April 2018
Accepted 1 May 2018
Available online 2 May 2018

Keywords:
Energy system analysis
Economic modeling
Hard-linking
Top-down and bottom-up
Energy-climate policy
Greenhouse gas emission reduction

ABSTRACT

In this paper we have hard-linked a bottom-up energy system model (TIMES) and a top-down computable general equilibrium model (REMES) in order to analyze both the energy system impacts and the economic impacts of reducing greenhouse gas emissions from transport. We study a limitation of CO_2 emissions from transport in Norway in 2030 to 50% of CO_2 emissions in 1990. The linked approach gives new insight both in terms of the technology mix and the emissions from different transport segments, ripple effects through the economy and regional welfare effects. Furthermore, the convergence of our full-link full-form hybrid model is relevant for comparison with soft-linked approaches.

1. Introduction

The transition towards a sustainable energy system affect a number of other sectors in the economy. This has created a need to better integrate energy system models with economic modeling. We have hard-linked a bottom-up energy system model, TIMES, and a top-down computable general equilibrium (CGE) model, REMES, in order to analyze both the energy system impacts and the regional economic impacts of reducing greenhouse gas emissions from transport. In our case study from Norway, future CO_2 emissions from transport in 2030 are limited to 50% of CO_2 emissions in 1990. The first contribution of the paper is related to the policy insight which suggests how ambitious emission reductions can be achieved in the transport sector. The second contribution is on the linking methodology building a hybrid approach. Before going in detail on that, we review existing literature.

Top-down CGE models describe the whole economy, and emphasize the possibilities to substitute different production factors in order to maximize the profits of firms and satisfy market clearance conditions. The proof of existence of a general equilibrium was established in Arrow and Debreu [1]. The first successful implementation of an applied general equilibrium model without the assumption of fixed input-output coefficients was made in 1960 by Leif Johansen [2], as noted by Dixon and Jorgenson [3]. A survey of well-known CGE models for sustainability impact assessments is presented in Böhringer and Löschel [4]. The substitution possibilities between energy and other production factors are captured in production functions, which describe the changes in fuel mixes as the result of price changes under certain substitution elasticities. The smooth CGE production functions can result in violation of basic energy conservation principles. The widely used constant elasticity of substitution (CES) production function aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy flows [5]. Top-down representations of technologies can also produce fuel substitution patterns that are inconsistent with bottom-up cost data [6].

Bottom-up engineering models describe energy supply from primary energy sources, via conversion and distribution processes to final energy use as well as interactions between these. In contrast to CGE models, they neglect the macroeconomic impact of energy policies, since they are partial equilibrium models and look only at

---

* Corresponding author.
E-mail addresses: per.ivar.helgesen@ntnu.no (P.I. Helgesen), arne.lind@ife.no (A. Lind), olga.ivanova@pbl.nl (O. Ivanova), asgeir.tomasgard@ntnu.no (A. Tomasgard).

https://doi.org/10.1016/j.energy.2018.05.005
0360-5442/

the energy market. Another weakness is that bottom-up models are unable to capture the full economy-wide rebound effects. They can easily capture substitution of energy carriers or technologies, but cannot anticipate demand increase due to income effects [7]. Bottom-up technologies for CO_2 abatement and the use of bottom-up and top-down models is thoroughly discussed by Grubb et al. [8], and an overview of hybrid modeling to shift energy systems toward more environmentally desirable technology paths is given by Hourcade et al. [9].

Hybrid models aim to combine the technological explicitness of bottom-up models with the economic richness of top-down models [10]. This can be accomplished in different fashions. Wene classifies model linking as either (informal) soft-linking or (formal) hard-linking [11]. Böhringer and Rutherford [12] do not use the term "hard-linking", but define three categories: 1) Coupling of existing large-scale models, 2) having one main model complemented with a reduced form representation of the other, and 3) directly combining the models as mixed complementarity problems. In this paper we adopt the terms *soft-linking* and *hard-linking* as defined by Wene, where soft-linking is information transfer controlled by the user and hard-linking is formal links where information is transferred without any user judgment (usually by computer programs). Furthermore, we use the term *integrated* when the models are combined into one, instead of exchanging information between separate model runs. Thus, we classify hybrid models as shown in Fig. 1.

One early example of *soft-linking* full models is described by Hoffman and Jorgenson [13], who couple an econometric macroeconomic model with a process analysis model of the energy sector. Later studies have focused on certain sectors, such as soft-linking between ETEM and GEMINI-E3 focusing on residentials [14], and between MARKAL and EPPA focusing on transport [15]. Recent publications attempt to link all economic sectors, for example between TIMES and EMEC [16] and between TIMES and GEM-E3 [17].

Many earlier linking experiments have been able to *hard-link* the models by simplifying or narrowing the focus in one of the models to defined parts of the economy. Some well-known examples of this type are the ETA-Macro model [18], MARKAL-Macro [19], MESSAGE-Macro [20] and TIAM-MACRO [21]. These applications have simplified the top-down model, while WITCH [22] on the other hand, has a simplified energy system model. Duan et al. [23] also describe a hybrid top-down model of China, with a bottom-up technical sub-model.

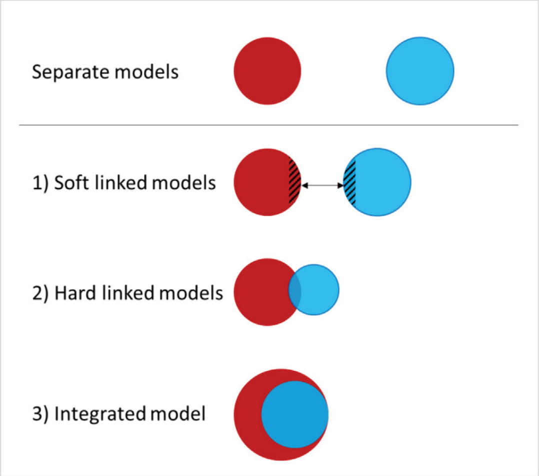

Fig. 1. Hybrid model variants.

Böhringer and Rutherford have been proponents for the *integrated* approach [10]. Böhringer [24] shows that bottom-up formulations of activity analysis can be integrated by formulating the general equilibrium problem as a complementarity problem. This type of approach was presented early by Scarf and Hansen [25], and further demonstrated by Mathiesen [26]. The approach is illustrated by Böhringer and Löschel [27], and Böhringer and Rutherford [12] present a decomposition procedure that also allows larger models to be solved. The integrated approach focuses on a selected sector in order to maintain tractability, and most contributions focus on electricity. Sue Wing [28] describes how to disaggregate the top-down representation into specific technologies in a manner consistent with the bottom-up characteristics. Proença and St. Aubyn [29] evaluate whether a feed-in tariff can be a cost-effective instrument to achieve a national target of renewable electricity generation, while Rausch and Mowers [30] examine the efficiency and distributional impacts of clean and renewable energy standards for electricity. Abrell and Rausch [31] study interactions between electricity transmission infrastructure, renewable energy penetration and environmental outcomes.

One argument for keeping the models intact instead of integrated is that top-down and bottom-up data are collected from different data sources and often with different product granulation and time resolutions. Bottom-up models focus on quantities and build on national energy balances, while top-down models deal with economic values and build on national accounts. In order to integrate models, data must be reconciled across models - which is highly advisable, but engineering and economic data are rarely consistent with each other [28]. By linking the models, we retain the consistency of each database. We keep the two models intact, and exchange relative information affecting demand, energy mix and capital growth.

Fortes et al. [17] use the terms "full-link" and "full-form" to characterize hybrid models. Full-link hybrid models cover all economic sectors, while full-form hybrid models combine detailed and extensive technology data with disaggregated economic structure. The state of the art in hybrid top-down bottom-up modeling reflected in the articles above is to use either soft-linked, full-link, full-form models, or integrated full-form models that focus on technical details in specific sectors. Our first contribution is to pursue a *hard-linked*, full-link, full-form approach, filling a knowledge gap between current state of the art practices.

In the literature above, the convergence of full-link full-form models is poorly investigated. Our approach eliminates two important drawbacks of soft-linked models: They are time and labour consuming to run, so convergence may not be tested stringently. Current state-of-the art articles have reported few iteration cycles and some observed convergence problems (see Krook-Riekkola et al. [16] section 4.1 and Fortes et al. [17] page 722, footnote 4). Whether full-link full-form models are able to reach convergence represents a knowledge gap. Our second contribution is therefore to utilize our hard-linked approach to check whether we are able to reach convergence using a full-link full-form approach.

Our third contribution is related to the case study, which is of high importance for Norwegian policy makers. While a 50% reduction of emissions from transport has been widely suggested by policy makers as a tool to meet Norwegian climate obligations [32], the feasibility and welfare effects has not been studied in the literature as far as we know. Our finding is that greenhouse gas emissions from transport may indeed be halved by transport technology investments, amounting to 6.5% reduction of income compared to a business-as-usual scenario. Regional utility reductions vary between 6.1% and 7.4% reduction of income.

As far as the authors are aware, our article represents the first hard-linking of large-scale stand-alone models employing a full-link with regional resolution and full-form bottom-up and top-down approach.

Our two models and their hard-linking is described in Section 2. Section 3 introduces the case study and presents results. We conclude in Section 4, where we also summarize the advantages of hard-linking.

2. The models and the linking

2.1. Description of the models

TIMES (**T**he **I**ntegrated **M**arkal **E**fom **S**ystem) is a bottom-up, techno-economic model generator for local, national or multi-regional energy systems [33]. A TIMES-model gives a detailed description of the entire energy system including all resources, energy production technologies, energy carriers, demand devices, and sectorial demand for energy services. The model assumes perfect competition and perfect foresight and is demand driven. The model aims to supply energy services at minimum total cost by making equipment decisions, as well as operating, primary energy supply and energy trade decisions.

A modified version [34] of TIMES-Norway [35] is used in the current work. The demand for various energy services, the techno-economic characteristics of energy technologies and resource costs and availability are given exogenously to the model. On the energy supply side, the following power production technologies are included: Hydropower (5 technologies), wind power (3 technologies), gas power with/without CCS (2 technologies), CHP plants (3 technologies) and waste heat recovery in industry (1 technology). Additionally, district heat may be generated by several different technologies (12 in total), such as oil, LPG and electric boilers. Transmission and distribution include high and low voltage grids, as well as district heating grids. The model has a wide range of demand sectors, including industry (11–14 sub-sectors per region), residentials (5 sub-sectors), services (8 sub-sectors), agriculture and transport (9 sub-sectors). The base year of the model is 2010 and the model horizon is to 2030. The time resolution covers all weeks during each year with five time-slices per week, giving 260 time-slices annually. Geographically the model covers Norway, and is divided into 5 model regions based on the pricing areas in the Nordic spot market for electricity [36]. There is exchange of electricity between regions and neighbouring countries, and the transmission capacity within and outside the model regions is given exogenously and is based on the current capacity. An overview of all energy commodities in TIMES-Norway is given in Table 8 in the Appendix.

Generally, the projected energy demand has to be given exogenously to the model [37], but due to the hard-linking of the two model approaches, the energy demand is now determined endogenously by REMES. The energy service demands of residential, service, industry and transportation are used as input to the TIMES-Norway model. The top-down model REMES is a **R**egional **E**quilibrium **M**odel with focus on the **E**nergy **S**ystem. REMES is a spatial CGE model. Consumers are demanding goods in order to maximize utility, and producers are supplying goods in order to maximize profits. A social accounting matrix (SAM) defines a benchmark equilibrium for the model. All the economic agents and goods are represented with accounts for all the economic transactions in a base year. Knowing this reference equilibrium, the model is able to adapt to shocks or policy changes like taxes, subsidies or endowment changes.

REMES focuses on the multiregional aspects, and works on the basis of fully balanced interregional SAMs with detailed interregional trade flows and transport margins. The model implementation allows for a flexible nesting structure. The nesting structure and substitution elasticities used in this study are presented in Appendix 7.2. We refer to the REMES model description in Ref. [38] for further details. The work has been inspired from several spatial CGE models such as PINGO [39], RAEM [40] and RHOMOLO [41]. Each agent in REMES is represented on the regional level, and comprise a representative household, a representative producer in each sector, a trader for each good acting according to the Armington assumption [42], a local government and a local investment sector.

We define production functions of the form ((KL)E)M in REMES (see Appendix 7.2 for further descriptions). We use elasticities as reported in Koesler and Schymura [43], but we assume a Leontief nesting of the energy goods. We refer to section 2.4, where we describe how we update the Leontief coefficients.

2.2. Design of the hard linking

Both the top-down and the bottom-up models have their own detailed databases. We keep both models intact, but have expanded them by accepting input from the other model (see Fig. 2). The exception is the adjustment of capital growth, which mandates homogenizing the absolute levels between model.

We do not attempt to define or restrict prices in REMES based on TIMES results, as done in Krook-Riekkola et al. [16] and Fortes et al. [17]. TIMES results should adjust technical aspects of REMES only.

One challenge is to define a data granulation that preserves the individual model strengths but allows an overlap enabling the linking between the models. The TIMES model gains from highly granulated data. In contrast, REMES is designed to work with aggregated data. The SAM describes an economic equilibrium where the use of production factors and available technologies are optimized simultaneously by different agents.

Preparations to accommodate hard-linking are:

1) Define data granularity for regions, sectors and commodities suitable for linking the top-down and the bottom-up model.
2) Define mappings between the model data structures (depending on step 1).
3) Describe nesting structure and substitution elasticities in top-down model (depending on step 1).
4) Preprocess top-down national accounts data to the data granularity defined in step 1.
5) Preprocess bottom-up national energy balance data to the data granularity defined in step 1.

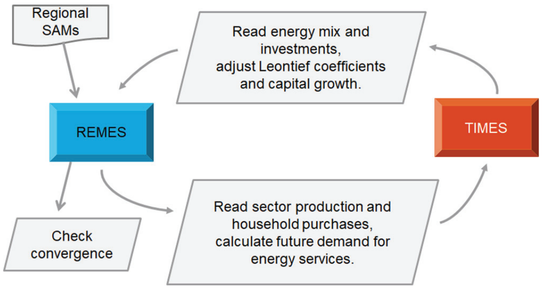

Fig. 2. Hardlinked models and mappings.

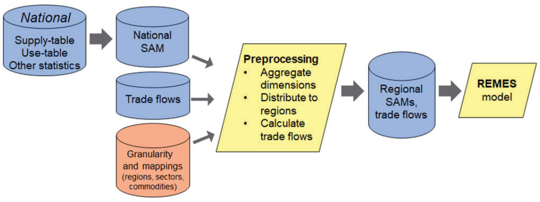

Fig. 3. Illustration of data input and preprocessing for the top-down model.

The preparation process for the top-down model is illustrated in Fig. 3.

We have defined four mappings, in order to couple the data dimensions: commodity (1 mapping), sector (2 mappings) and geographic region (1 mapping). Instructive examples of the data mappings are provided in Table 7 in the Appendix. The regions in the models are the same in our application, so the regional mapping is only necessary to link the different regional codes. Sector mappings are directional, as in Krook-Riekkola et al. [16], see Fig. 4 below.

In order to achieve a full-link, full-form and hard-linked approach, we have simplified the time dimension. We run a static version of the REMES model and assume a linear development of demand for energy services from base year to horizon year in TIMES. We harmonize time assumptions in the setup of the models, such that growth assumptions in REMES match the planning horizon in TIMES. Let us exemplify: In TIMES we have used a base year of 2010 and a horizon year of 2030, see Fig. 5. We calculate an economic shock in REMES based on yearly growth rates for capital and labour growth, provided in national projections. Let γ represent the yearly capital growth and let λ represent the yearly labour growth. In REMES we assume a capital growth equal to $(1+\gamma)^{(2030-2010)}$ and a labour growth equal to $(1+\lambda)^{(2030-2010)}$. The REMES solution for 2030 determines the demand for energy services in TIMES throughout the model period, and the TIMES solution for 2030 then determines the energy mix in REMES in 2030.

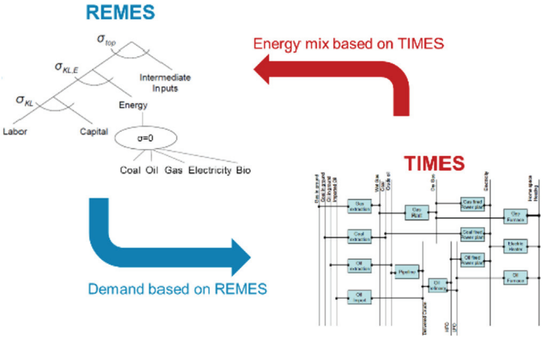

Fig. 4. Directional sector mappings.

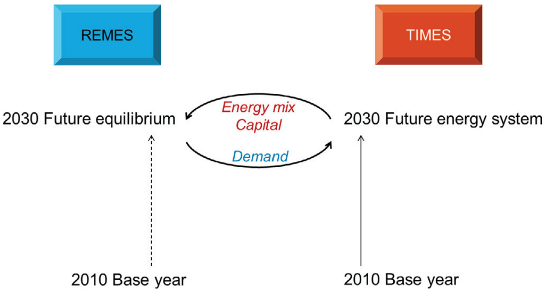

Fig. 5. Time dimension, linking the static REMES model with the dynamic TIMES model.

When a sector produces more, we assume that demand for energy services increase proportionally, keeping the same energy intensity. Assumptions about decreasing or increasing energy intensities can easily be implemented as well.

Sets	
R	regions in top-down model, indexed by r, mapped by subsets R'_r
R'	regions in bottom-up model, indexed by r', mapped by subsets R'_r
C	energy commodities in top-down model, indexed by c, mapped by subsets $C_{c'}$
C'	energy commodities in bottom-up model, indexed by c' mapped by subsets C'_c
S	sectors in top-down model, indexed by s, mapped by subsets $S_{s'}$
S'	energy service demand sectors in bottom-up model, indexed by s', enumerates relevant energy services[1]
P'	processes in bottom-up model providing energy service, indexed by p', mapped by subsets P'_s
T'	time periods in bottom-up model, indexed by t'
TS'	time-slices in bottom-up model, indexed by τ'
Mapping parameters	
$k_{s,s'}$	demand factor mapping top-down sector activity to bottom-up energy service demand
$\mu_{p',s}$	distribution of bottom-up energy use in process p' towards top-down sector s

Examples of the four mappings are provided in Section 7.5 in the Appendix.

2.3. From REMES to TIMES: energy service demand

REMES provides input about total energy demand to TIMES. We assume there are specific energy intensities for each industry in each region, measuring input of energy service per production quantity. Energy services consists of heating, cooling, electricity specific, transport and energy in the form of raw materials.

We define the following notation:	
$TDem_{r',t^{base},s'}$	base year demand for energy service in bottom-up model for sector s' and region r'
$XD_{r,s}$	sector production from top-down model in region r and sector s
$HOUS_{EXP_r}$	household expenditure from top-down model in region r
$\alpha_{r',s'}$	demand growth factor based on top-down model
$TDem_{r',t',s'}$	calculated demand in bottom-up model region r', period t', energy service demand sector s'

The demand in TIMES is calculated as:

$$TDem_{r',t',s'} = TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)}$$

The demand growth factor is based on REMES:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}, s \in S_{s'}} \frac{\left(XD_{r,s}^{future} - XD_{r,s}^{base}\right)}{XD_{r,s}^{base}} k_{s,s'}$$

Most TIMES demands are mapped from one relevant REMES sector acting as demand driver, and a natural default value for the mapping factor $k_{s,s'}$ is 1, retaining the same energy intensity in the future as in the base year.

In the tertiary sector we assume that new buildings in education, health and social services, hotel and restaurant, offices, wholesale and retail are expected to have lower energy demands, and these growth factors are scaled down based on regulations on technical requirements for building works. We assume that new requirements will lead to lower energy services demand, but that some buildings will also lag behind due to lack of refurbishment.

The factor $k_{s,s'}$ allows to make demand growth dependant of more than one REMES sector, and pooling these together. Values of $k_{s,s'}$ must then be scaled accordingly.

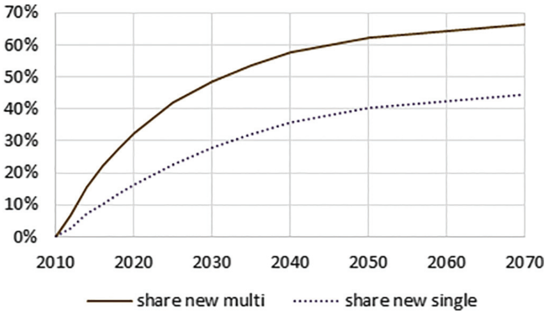

Fig. 6. Share of new buildings in building stock.

For new houses,[2] we calculate demand for heating as

$$TDem_{r',t',s'} = \left(TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)} \right) \psi_{t,s}\phi_{s'}, \quad s' \in S'$$

For existing houses,[3] we calculate demand for heating as

$$TDem_{r',t',s'} = \left(TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)} \right) (1 - \psi_t), \quad s' \in S^{household' heating}$$

2.3.1. Households

For households we assume specific energy service intensities for each region, measuring input of energy service per household expenditure. Energy services consists of heating and electricity specific energy demand.

Household expenditure from REMES is used as driver for energy services demand in TIMES. We calculate alpha coefficients for single-family houses, multi-family houses and cottages:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}} \frac{\left(HOUS\_EXP_r^{future} - HOUS\_EXP_r^{base}\right)}{HOUS\_EXP_r^{base}} k_{HOUS,s'}$$

The factor $k_{HOUS,s'}$ acts as an income elasticity. We assume heating to be a normal and necessity good with income elasticity between 0 and 1, while electricity is assumed to be a luxury good with income elasticity above 1. In this study we have assumed income elasticities of 0.99 for heating and 1.01 for electricity in existing single-family and multi-family houses.

Energy demand for heating is expected to decrease more sharply in new buildings, due to strengthened regulations and improved building techniques. We assume that heating demand decrease by 23% in new single-family houses and by 25% in new multi-family houses, captured by the two factors $\phi_{single-family} = 0.77$, and. $\phi_{multi-family} = 0.75$.

Furthermore, we assume certain shares $\psi_{t,s'}$ of new single-family and multi-family houses per year during the planning period, see Fig. 6.

Electricity-specific demand in households is calculated accordingly, only without the use of the heat specific factor ϕ.

2.3.2. Transport

TIMES focuses on transport demand groups with exogenous demand, and associated transport technologies. Demand for transport services in REMES is determined by the amount of inter-regional trade multiplied with inter-regional transport and trade margins and direct consumption of transport services by households and firms.

Demand growth factor $\alpha_{r',s'}$ is based on REMES:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}, s \in S_{s'}} \frac{\left(XD_{r,s}^{future} - XD_{r,s}^{base}\right)}{XD_{r,s}^{base}} k_{s,s'} + \sum_{r \in R_{r'}} \frac{\left(HOUS\_EXP_r^{future} - HOUS\_EXP_r^{base}\right)}{HOUS\_EXP_r^{base}} k_{HOUS,s'}, \quad s' \in S^{trans'port}$$

---

[1] H = heat, E = electricity specific, M = materials, C = cooling, T = transport.

[2] The s'index used in TIMES enumerates both energy service (heating versus electricity specific) and household type (single-family versus mult-family).

[3] We assume that refineries transform crude oil into heavy, medium and light distillates in fixed proportions.

Table 1
Transport linking demand factors from REMES to TIMES.

REMES (s)	TIMES (s')	$k_{s,s'}$ coefficient	TIMES unit
Air transport (TAIR)	Air transport (TAIRT)	1	GWh
Railway transport (TRAI)	Train transport (TPUTT)	1	GWh
Sea transport (TSEA)	Sea transport (TSEAT)	1	GWh
Agriculture (AAGR)	Other transport (TOTHT)	1	GWh
Construction (CCON)	Other transport (TOTHT)	1	GWh
Land transport (TLND)	Bus transport (TPUBT)	0.5	Mv-km [a]
Households (HOUS)	Long distance cars (TCART-L)	1.416	Mv-km
Households (HOUS)	Short distance cars (TCART-S)	1.231	Mv-km
Land transport (TLND)	Short distance cars (TCART-S)	0.05	Mv-km
Land transport (TLND)	Heavy duty freight (TFRET-H)	2	Mv-km
Land transport (TLND)	Light duty freight (TFRET-L)	2	Mv-km

[a] Million-vehicle-kilometers.

The transport linking demand factors $k_{s,s'}$ are provided in Table 1.

$$\lambda_{r,c,\mathrm{HOUS}} = \frac{\sum_{r'\in R_r, p'\in P'_{HOUS}, c'\in C_c, \tau'\in T} \left(Flo_{r',t_{future},p',c',\tau'} \cdot \mu_{p',s}\right)}{\sum_{r'\in R_r, p'\in P'_{HOUS}, c'\in C_c, \tau'\in T} \left(Flo_{r',t_{base},p',c',\tau'} \cdot \mu_{p',s}\right)} \cdot \frac{HOUS\_EXP_r^{base}}{HOUS\_EXP_r^{future}}$$

2.4. From TIMES to REMES: energy mix

We assume Leontief production technology with fixed input factors for energy inputs in the spatial CGE model. Leontief coefficients of the production functions are calibrated on the data from inter-regional SAMs.

We adjust Leontief coefficients of energy inputs in REMES, based on TIMES quantities. This adjustment constitutes a different shock to REMES (additional to growth in labour and capital). Factors for relative development of energy carriers as input to REMES production sectors and end use per region are calculated by comparing TIMES's flows of energy carriers in the future year against the base year. However, we do not adjust Leontief coefficients of the energy production sectors in the top-down model. This choice is due to the unique structure of the Norwegian SAM. We consider the various petroleum products as a cluster in the SAM.[3] Then there are few intermediate energy goods flowing between energy producing sectors. For example, electricity production in Norway is approximately 100% renewable, for the most based on hydropower. Electricity supply is independent of coal, oil and gas. This makes the Norwegian power sector independent of the rest of the energy production sectors. However, if such substitution effects are important in an economy, an update scheme for these Leontief factors may need to be implemented.

We define the following notation:

$Flo_{r',t',p',c',\tau'}$	flow of energy in bottom-up model of energy commodity c' in process p' in region r' during time period t' and time-slice τ'
$\lambda_{r,c,s}$	Leontief adjustment factor changing use of energy commodity c in sector s in region r based on bottom-up model
$cost_{adj_{r,s}}$	cost adjustment factor in top-down model, rescaling Leontief factor in order to isolate substitution effect from energy commodities
$leontief^{base}_{r,c,s}$	Leontief factor in top-down model base year SAM
$Leontief_{r,c,s}$	calculated Leontief factor in top-down model in region r of energy commodity c in sector s

Leontief adjustment factors for top-down sectors are calculated as:

$$\lambda_{r,c,s} = \frac{\sum_{r'\in R'_r, p'\in P'_s, c'\in C_c, \tau'\in T} \left(Flo_{r',t_{future},p',c',\tau'} \cdot \mu_{p',s}\right)}{\sum_{r'\in R'_r, p'\in P'_s, c'\in C'_c, \tau'\in T} \left(Flo_{r',t_{base},p',c',\tau'} \cdot \mu_{p',s}\right)} \cdot \frac{XD^{base}_{r,s}}{XD^{future}_{r,s}}$$

The last fraction adjusts for growth in the sector as a whole. If the use of oil in the construction sector increase by 10%, but the construction sector also grows by 10%, then the relative use of oil remains unchanged. The corresponding formula for households is shown below.

As we prefer to keep each model with data intact, we do not attempt to harmonize the data. If TIMES has zero energy flow in the base year, we still calculate a growth factor from the first intermediate year where TIMES calculates a flow. If TIMES does have energy flow in the base year but zero energy flow in the horizon year, we calculate a zero factor as input to REMES – as opposed to the situation where TIMES does not use the energy carrier and we do not use an adjustment factor in REMES (a zero value operates differently from no value.) If TIMES does not have a flow in either the base year or the future/horizon year, we do not consider flows in intermediate years and avoid any adjustment on the corresponding Leontief-factor that might exist in REMES.[4] If TIMES utilizes an energy flow in the horizon year only, we assume a λ growth factor value of 2.

Energy flows in TIMES may evolve from a marginal level, and produce high λ growth factor values, which may cause problems in REMES. If the shock is too severe, REMES may fail to find a solution. We limit the λ growth factor to a value of 400.

The calculations described thus far will adjust the regional

---

[4] We have experienced cycling behavior during iterations when we adjust Leontief factors in such situations.

Table 2
Mapping energy use from transport processees in TIMES to REMES sectors.($\mu_{p',s}$).

TIMES process	REMES sectors			
Bus transport (TPUB*)	100%	Land transport (TLND)	–	(n.a.)
Train transport (TPUT*)	100%	Land transport (TLND)	–	(n.a.)
Sea transport (TSEA*)	100%	Sea transport (TSEA)	–	(n.a.)
Other mobile combustion (TOTH*)	67%	Agriculture (AAGR)	33%	Construction (CCON)
Air transport (TAIRT*)	99%	Air transport (TAIR)	1%	Households (HOUS)
Heavy freight (TFRET*-H)	100%	Land transport (TLND)	0%	Households (HOUS)
Light freight (TFRET*-L)	99%	Land transport (TLND)	1%	Households (HOUS)
Short distance cars (TCART*-S)	15%	Land transport (TLND)	85%	Households (HOUS)
Long distance cars (TCART*-L)	1%	Land transport (TLND)	99%	Households (HOUS)

energy mix for each sector, and produce both substitution effects and income effects. Our primary aim is to capture the changed energy mixtures. We rescale the costs of the adjusted energy mix to become equal to the costs of the original energy mix, in order to isolate the substitution effects.

$$cost\_adj_{r,s} = \frac{\sum_{c \in C}\left(leontief^{base}_{r,c,s}\right)}{\sum_{c \in C}\left(leontief^{base}_{r,c,s} \cdot \lambda_{r,c,s}\right)}$$

$$Leontief_{r,c,s} = cost\_adj_{r,s} \cdot \lambda_{r,c,s} \cdot leontief^{base}_{r,c,s}$$

Regarding autonomous energy efficiency improvements (AEEI), REMES rely on TIMES data input on expected new future technologies and exploit TIMES results to capture future relative use of energy carriers. In this study we focus on substitution effects, and employing income effects from the adjusted energy mix is left for future research.

Transport in REMES is modelled differently from TIMES. REMES focuses on commercial transport, while household own production of transport is not captured by any other value transfer than fuel demand. Some energy flows in TIMES serves processes (for example transport technologies) which naturally belong to multiple sectors in REMES. We assume for example that most long-distance car transport (99% of the kilometres) in TIMES are demanded by households in REMES, while 15% of short distance car kilometres are driven as part of land-based commercial transport in REMES. Table 2 shows mapping of transport related energy flows from TIMES processes to REMES sectors.

In this study we put the policy goal[5] into TIMES as a restriction, which triggers higher investments. We assume that the investment increase reduces capital growth in REMES accordingly.

We define the following notation:

$KS^{base}_{r,s}$	capital income in top-down model in region r and sector s in base year
$ncapcost_{r',t',p'}$	capacity investment cost in bottom-up model for process p' in time period t' and region r'
$CapitalRemes_r$	estimated capital value in bottom-up model in region r
$NCAP_{r',t',p'}$	capacity investments in bottom-up model region r' time period t' process p'
$shockadj^{CO2K}_r$	calculated capital growth adjustment factor in top-down model for region r

Our social accounting matrix (SAM) holds capital income by region and sector in the base year ($KS^{base}_{r,s}$). The perpetuity value of the capital income would overestimate the capital value, and we add a factor κ to adjust for capital depreciation:

$$CapitalRemes_r = \frac{\sum_s KS^{base}_{r,s}}{df \cdot \kappa}$$

where df is the real discount factor used in TIMES. We assume $df = 4\%$ and $\kappa = 2$, these values produce a coarse capital estimate which corresponds with national estimates of real capital and net national wealth per capita.[6] For a discussion of discount rates in energy system models, see Garcia et al. [44].

We calculate adjustment factors for capital shocks in REMES based on TIMES investments like this[7]:

$$shockadj^{CO2K}_r = \frac{CapitalRemes_r - \sum_{r' \in R'_r, t' \in T', p' \in P'} ncapcost_{r',t',p'}\left(NCAP^{CO2K}_{r',t',p'} - NCAP^{BAU}_{r',t',p'}\right)}{CapitalRemes_r}$$

2.5. Linking capital from TIMES to REMES

Changes in Leontief coefficients are typically favourable, meaning that less energy input is required to achieve the same production as before due to expected technological progress. These improvements require investments into capital stocks of the production sectors. Linking TIMES investments and REMES capital stocks requires absolute instead of relative levels. We must establish a harmonized baseline of capital stocks between the models, and we make the assumption that the scale of investments in a business as usual (bau) scenario is compatible with the capital stocks growth of REMES.

2.6. Convergence

We calculate the relative change of variable values between iterations, and compares it against a chosen tolerance. If all changes are below the tolerance, the iterations have converged. Examples for commodity prices and sectoral output are shown below (where

---

[5] Reducing CO_2 emissions from transport.

[6] Long-term Perspectives on the Norwegian Economy 2013, white paper from Norwegian Ministry of Finance.

[7] For simplicity, we have not displayed currency indexes in the formula, as we only use one currency in this study.

index i indicates iteration number).

Commodity prices: $\max_{r,c}\left(\frac{\left|P^{i}_{r,c}-P^{i-1}_{r,c}\right|}{\left(P^{i-1}_{r,c}\right)}\right) \leq$ tolerance.

Sectoral output: $\max_{r,s}\left(\frac{\left|XD^{i}_{r,s}-XD^{i-1}_{r,s}\right|}{\left(XD^{i-1}_{r,s}\right)}\right) \leq$ tolerance.

We calculate the relative change of the following variables, to assess whether iterations have converged with tolerance 10^{-5} (see Fig. 14): Commodity prices, sectoral output, household consumption, sectoral labour use, price of labour, price of capital, total energy system cost, consumer welfare, public welfare, investor welfare as well as hicksian prices of consumer welfare, public welfare and investor welfare.

3. Analysis and results

3.1. Scenarios and data

In our analysis we restrict emissions of CO_2 from transport in 2030 to 50% of CO_2 emissions in 1990, corresponding to suggestions by National transport agencies [32].

The CO_2-restriction is imposed in TIMES, and mandates the use of new technologies and energy carriers. We run a business-as-usual scenario (*bau*) without the CO_2-restriction, and a CO_2-reduction scenario (*co2*) with the naïve assumption that TIMES investments do not affect available capital growth in REMES. We run a third scenario (*co2k*) where we restrict CO_2 emissions and make the assumption that TIMES investments exceeding those in the *bau* scenario will reduce available capital growth in REMES.

The *co2k* scenario resembles a techno-optimistic policy where national authorities finance technological shifts to reach the common target of the society, while societal actors can behave as before. These technological investments demand capital, which could have served society better if used alternatively. In the *co2k* scenario we calculate Hicksian compensating variation per region, to quantify the amount of additional income households would mandate to compensate for their utility loss compared to the *bau* scenario.

The current policy for zero emission vehicles in Norway shares important characteristics of the *co2k* scenario. Government has provided powerful financial incentives: Battery electric vehicles and fuel cell electric vehicles are exempt from registration tax, value added tax and road tolls, pay a lower annual fee, are allowed to drive in the bus lane, enjoy free parking in municipal car parks and run free on ferries [45]. A thorough review of Norwegian incentives is provided by Figenbaum et al. [46].

We also compare stand-alone TIMES solutions based on exogenous demand with the hard-linked iterative TIMES solutions. Exogenous demand for energy services are taken from the CenSES national energy demand projection (see Ref. [47]).

3.1.1. Growth assumptions

We have used expected yearly growth rates for capital and labour from the government white paper “Long-term Perspectives on the Norwegian Economy 2013”, and regionalized these according to Statistics Norway's official population projection (MMMM).

3.1.2. The continental shelf

Norway has an extensive production of oil and gas from the continental shelf, with high production, no households and highly specialized transportation needs. We have chosen to attach the continental shelf to the northern region of Norway, as this is the outermost region with the lowest population. Our results are presented without this combined region, but full results are available in a downloadable Appendix.

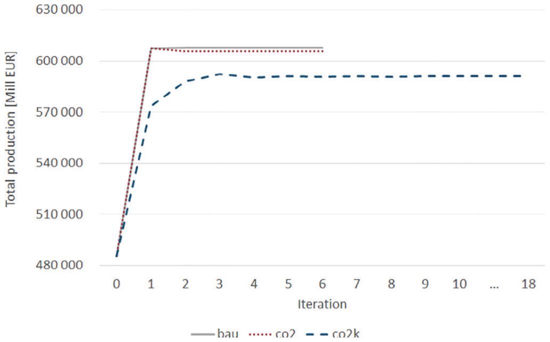

Fig. 7. Value of total production in 2030 in REMES by scenario per iteration (iteration 0 shows production in base year 2010 for comparison).

3.2. Results

Fig. 7 shows that changes in energy mix from scenario *bau* to *co2* has a small impact in the REMES model, and that few iterations are needed to reach convergence. Linking capital investments in scenario *co2k* has larger impacts, and more iterations (18 compared to 6) are required to achieve convergence. REMES calculates a significant growth in total yearly production from the base year (represented by iteration 0) to iteration 1, reflecting the changes between year 2010 and 2030. The production growth in our scenarios *bau* and *co2* are quite similar. The only difference in REMES between these scenarios is the energy mix feedback from TIMES. In scenario *co2k* investments in TIMES reduce available capital growth in REMES. Having less available resources reduces production potential, household income and demand for goods and services, and the value of total production decreases by 2.8% compared to *bau*. This reduction influences the demand for energy services in TIMES and the total energy system costs, which Figs. 7 and 8 show.

Fig. 8 shows total system costs in TIMES, which grows considerably from the *bau* to the *co2* scenario while the *co2k* scenario ends somewhere in between. The constraint on CO_2 emissions from transport leads to higher investments in new technologies in TIMES. In scenario *co2k* these investments reduce production in REMES. Then demand for energy services decreases, and energy system costs in scenario *co2k* decrease compared to *co2*.

The capital linking provides important feedback and causes oscillations between the models. Total production in REMES (Fig. 7) and energy system costs in TIMES (Fig. 8) appear to be inversely correlated in scenario *co2k*, because increased costs in TIMES limit the growth in REMES.

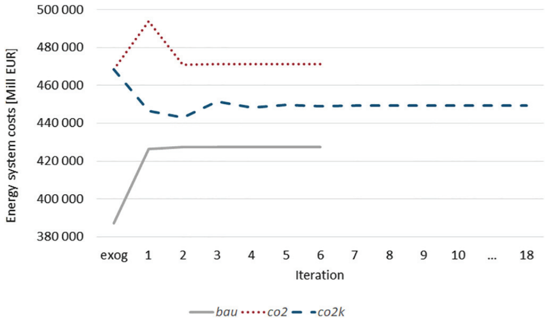

Fig. 8. Total aggregated energy system costs in TIMES by scenario per iteration (the first iteration is based on exogenously given demand).

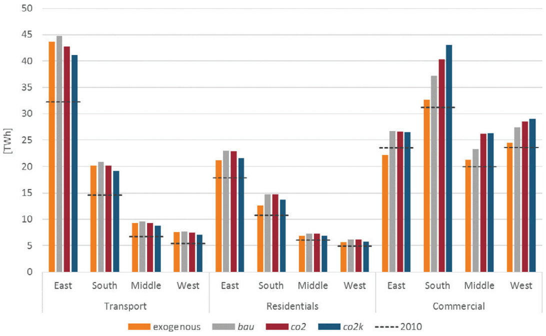

Fig. 9. Projected demand for energy services in 2030 per scenario, region and aggregated sector, compared to 2010 (TWh).

In the first iteration (exog), energy service demand is given exogenously to TIMES from a national projection. We see that energy system costs increase significantly in iteration 1 in both *bau* and *co2*. The reason is that demands derived from REMES are higher than the exogenous demand in these scenarios, as we will see in Fig. 9.

System costs in the *co2* scenario bounce back in iteration 2, due to changes in energy mix that REMES recognizes at this point. Further iterations appear to produce small movements after iteration 2 in scenarios *bau* and *co2*. This shows that energy mix feedback from TIMES to REMES has effects, but they are minor compared to the effects from the capital linkage. Keep in mind that we rescale Leontief coefficients to avoid income effects from the revised energy mix. We have seen that introducing such income effects have greater impacts than the isolated substitution effects of energy carriers.

3.2.1. Energy service demand

Fig. 9 illustrates the demand in 2030 for the three main scenarios as well as the exogenous projection, divided into transport, residential and commercial (consisting of primary sector, manufacturing and services). In the *bau* scenario, the demand is higher than the exogenous projection in all sectors and all regions. In the *co2* scenario, the transport demand is reduced compared to *bau*, and the demand is reduced even further in the *co2k* scenario. For the residential sector, the demand in the converged solution is more or less identical in the *bau* and *co2* scenarios, which is higher than the exogenous projection. The *co2k* scenario experiences a slight increase in all regions for the residential sector compared to the exogenous projection.

For the primary sector, manufacturing and services (labelled "commercial" in Fig. 9), the demand increases in all the scenarios compared to the exogenous projection. This can especially be seen in region South, but the increase is also significant in the other regions.

One might ask how demand for energy services in the commercial sector can increase going from *bau* to *co2* and *co2k*? CGE models are highly nonlinear, and our application includes many adjustments happening jointly. These adjustments lead to diverse effects across sectors and regions. The demand for energy services does not follow directly the aggregated production in REMES, since 1) activity levels and prices in disaggregated sectors shift differently and 2) sectors have different energy intensities. Total demand for energy services in fact increases from *bau* to *co2*, even though production decreases. One reason is that the price of several energy carriers decreases.

Table 3
Regional growth rates for labour and captial.

Region	2010 population	2030 projection	Labour growth 2010–2030	Capital growth 2010–2030
East	2 000 176	2 560 530	18%	53%
South	1 181 781	1 489 341	16%	50%
Middle	670 073	814 900	12%	45%
West	530 408	658 994	15%	48%
North	445 333	486 861	1%	30%
Total	**4 827 771**	**6 010 626**	**15%**	**49%**

Since CO_2 emissions from transport are constrained in the *co2* and *co2k* scenarios, the transport sector has to invest in new technologies. The transport energy mix shifts to new and more expensive energy carriers without emissions. Fossil energy carriers on the other hand get cheaper, creating growth opportunities in other sectors.

As shown in Table 3, we assume a higher capital growth than labour growth. The price of capital decreases, while the price of labour increase. Capital intensive manufacturing sectors are able to grow more than labour intensive service sectors. The commercial sectors with highest growth are aluminium, chemicals and metals. These sectors are also energy intensive, and are the main reasons that demand for energy services increases.

Furthermore, we assume that the capital growth is given per region, and transport investments hit different regions with different strength (see Table 5 in the Appendix).

Table 5 in the Appendix shows that the South region is the relatively least affected by the investments in transport technologies, and thus has relatively more capital growth left to spend in the economy. Region South increases activity in energy intensive sectors, and this leads to the significant increase in energy demand in Fig. 9.

This kind of response may at first be considered counterintuitive. In our opinion these results are a good example that a hybrid top-down and bottom-up approach may provide new knowledge.

3.2.2. CO_2 emissions

Fig. 10 shows the CO_2 emissions in 2030 from the transport sector in the three scenarios. Emissions based on exogenous demand and the converged solution as well as the first three iterations are included. As seen, the emissions in 2030 are restricted in

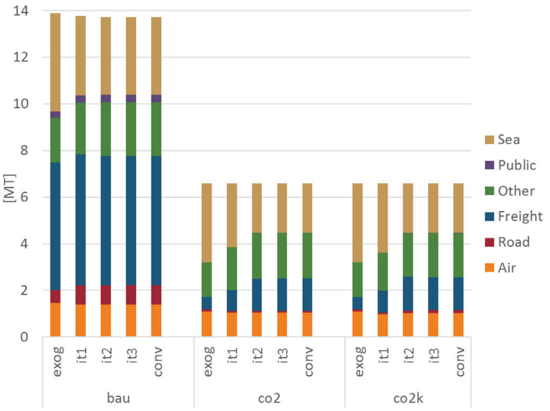

Fig. 10. CO_2 emissions from transport in 2030.

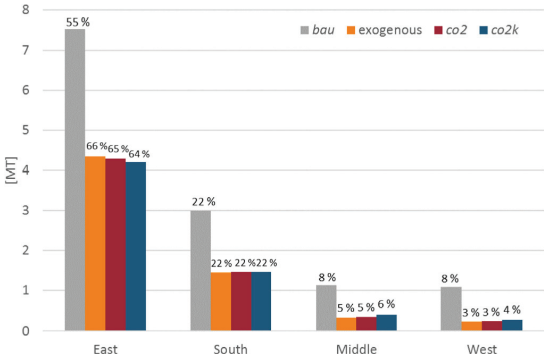

Fig. 11. CO_2 emissions from transport in 2030 by region (converged solution). Relative figures (above bars) indicate regional contribution for the respective scenario.

both of the CO_2 reduction scenarios. The total national emissions related to transport are reduced to 6.6 Mt in 2030.

For both of the CO_2 reduction scenarios, the same trend is observed during the iterations. In the exogenous demand solution, emissions from sea transport account for approximately 50% of the total emissions. In the linked approach, emissions from other transport modes are highest, followed by sea transport. As seen, CO_2 emissions from freight transport increase during the iterations. There are relatively small differences between the *co2* and the *co2k* scenario. The former has slightly higher emissions from air and other, whereas the *co2k* scenario has higher emissions from road transport (i.e. cars).

In the *bau* scenario, the total national emissions decrease slowly from 15.6 Mt to 13.7 Mt in 2030. The reason for this reduction is that several new transport technologies are being used in the *bau* scenario, reducing the use of e.g. conventional diesel and gasoline engines.

Regional CO_2 emissions in 2030 from the transport sector are illustrated in Fig. 11. 55% of the emissions in the *bau* scenario are related to transport activity in the east region, followed by 22% in region south. The solution based on exogenous demand allows region East to emit more CO_2 than the two hard-linked solutions, while the other regions show an opposite pattern.

3.2.3. *Energy system investments*

Fig. 12 illustrates energy system investments in transport technologies in the planning period. The upper part shows investments that only occur in the CO_2-constrained scenarios, while the lower part shows the largest investments in *bau* as well. It is evident that the CO_2-constraint triggers large investments.

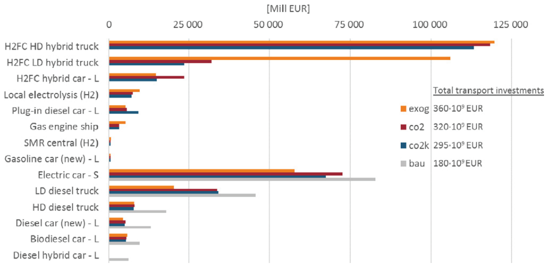

Fig. 12. Total transport investments comparing the CO_2 constrained scenarios with the bau scenario (H2FC = hydrogen fuel cell, HD = heavy duty, LD = light duty, L = long distance and S = short distance).

In the CO_2-constrained scenarios, a massive increase in the use of hydrogen based light (LD) and heavy duty (HD) trucks are experienced. At the same time, the use of conventional diesel trucks is reduced. For heavy duty freight transport, massive investments in hydrogen vehicles occur in 2030, whereas for light duty trucks, the investments include a combination of gasoline, diesel and hydrogen vehicles. Another main difference between *bau* and the CO_2 constrained scenarios is the reduced use of diesel for long distance car travels. The majority of the traditional diesel cars are replaced by investing in either plug-in hybrid diesel cars or hydrogen fuel cell cars. As seen in Fig. 12, increased investments are also experienced in various hydrogen production technologies like electrolysis (mostly) and steam reformation of natural gas. In the *co2k* scenario, all hydrogen investments are made in 2030, whereas *co2* and *exog* starts in 2020 with hydrogen long distance cars and reformation of natural gas. A reduction in investments in electric vehicles for short distance travels is seen in the CO_2 constrained scenarios. This is due to reduced demand for short distance travels, and not because other technologies are being used.

Fig. 12 shows that in the CO_2-constrained solution based on exogenous demand (*exog*), hydrogen based light duty trucks are used heavily. Transport investments in *exog* are 65 000 million Euro higher than in *co2k*. This is an indication that estimated investment costs based on inflexible exogenously given demand projections could vary greatly.

3.2.4. *Regional welfare analysis*

Our models do not directly calculate environmental benefits from reaching the policy goal of reduced CO_2 emissions, they only assess economic costs of such policies. This means that we would need to compare the economic costs with the environmental benefits for full societal cost-benefit analysis of the policy scenarios. Here we use the Hicksian compensating variation (CV) [48] as a monetary measure of welfare loss. The CV takes the *co2k* equilibrium incomes and prices, and calculates how much income must be added in order to keep households at their *bau* utility level. Because our utility function is linear homogenous, the Hicksian compensating variation is computed as

$$CV_r = \frac{\left(U_r^{bau} - U_r^{co2k}\right)}{U_r^{co2k}} I_r^{co2k}$$

Table 4 shows that the East region has the highest compensating variation, but its welfare loss as a percent of income is lowest of all. Regions South and West experience the highest welfare losses, compared to the *bau* scenario. Interestingly, the Middle region that loses the highest share of its capital growth still suffers less than the South and West regions.

We are able to track the CV during iterations, as shown in Fig. 13.

Welfare losses are substantially higher during the first iterations. Eventually the hard-linked models converge to an equilibrium, where region South in particular has reduced its welfare loss compared to the initial iterations.

Welfare losses in the *co2k* scenario are corresponding to 6.5% of the household income in the *bau* scenario. These figures may seem high. One reason is our conservative choice regarding the costs of the adjusted energy mix. In this study we rescaled the costs of the adjusted energy mix to become equal to the costs of the original energy mix, in order to isolate the substitution effects and neglect uncertain income effects from autonomous energy efficiency improvements (AEEI).

Comparing scenarios *co2* and *co2k* suggests however that income effects provide greater impacts than substitution effects. We

Table 4
Hicksian compensating variation (CV) per region.

Region:	East	South	Middle	West	Total
Household utility					
Bau	1.514	1.629	1.434	1.490	(n.a)
co2k	1.421	1.507	1.341	1.380	(n.a)
Price of utility					
Bau	1.032	1.037	1.020	1.025	(n.a)
co2k	1.023	1.027	1.010	1.015	(n.a)
Income [*mill EUR*]					
bau	94 295	27 892	22 450	21 290	165 928
co2k	87 739	25 544	20 788	19 523	153 594
Hicksian Compensating Variation [*mill EUR*]	5 750	2 066	1 442	1 569	10 826
Hicksian CV as share of *bau* income	6.1%	7.4%	6.4%	7.4%	6.5%

suggest that AEEI improvements in the top-down model could be assessed based on results from the technologically more detailed bottom-up model. Preliminary experiments have indicated that income effects from energy efficiency improvements in the bottom-up model are significant, but these results require further investigations which fall outside the scope of this study and is left for future research.

3.2.5. *Convergence*

Fig. 14 shows convergence results from the three scenarios. Each scenario run reaches the chosen tolerance set at 10^{-5} as the largest relative variable deviation between iterations.

The *bau* and *co2* scenarios reach convergence faster than the *co2k* scenario, which also links capital growth. The first two scenarios reach convergence after 6 iterations, whereas *co2k* needs 18 iterations. Computer running times are provided in Appendix 7.4.

We have observed situations where convergence was not reached because of cycling due to two different reasons:

- Macro level: The top-down model found different equilibria, and alternated between these in different iterations. Convergence could be reached or not, depending on starting points and how the solutions progressed during iterations. We were able to avoid this behavior by removing one unintended degree of freedom to the model and narrow down the solution space to one unique equilibrium. Still, the general problem class does not rule out the possibility of non-uniqueness, in which case the top-down model might find alternative equilibria.
- Micro level: Leontief coefficients could alternate between iterations, creating oscillation. This phenomenon was avoided by generalizing the Leontief adjustment calculation, capturing situations where an energy carrier went out of the energy mix, and then returned into the mix due to an undefined Leontief adjustment factor.

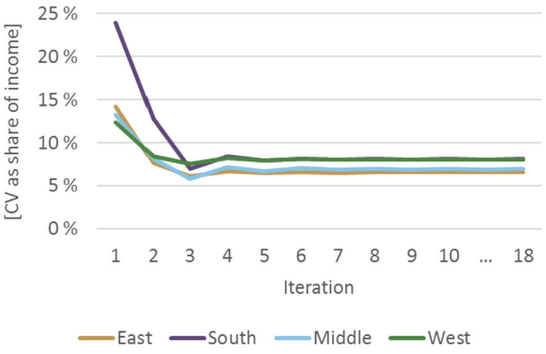

Fig. 13. Compensating variation per region and iteration.

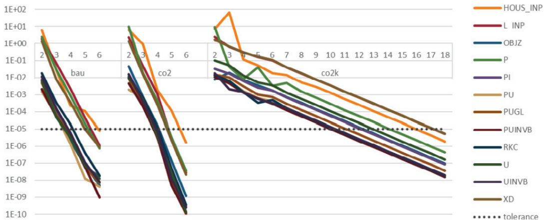

Fig. 14. Largest relative variable deviations per scenario until convergence.

An important strength of our hard-linked approach is the ability to detect such situations. First, whether most CGE models possess a unique equilibrium or whether multiplicity usually simply goes undetected is an open question [49]. Second, iteratively updating the models may lead to unanticipated responses with unrealistic effects, which are desirable to detect and prevent.

4. Conclusions

We have implemented hard-linking between a computable general equilibrium complementarity model (REMES) and an energy systems model (TIMES). This enables us to define sectoral energy policy measures and investigate ripple effects through the economy and regional welfare effects. The methodology developed in this paper represents a general and robust linking between top-down and bottom-up models using a full-link full-form approach.

Soft-linking will often lead to lower data granularity, and manual procedures will typically limit the number of iterations, resulting in less rigid convergence criteria. In this study using hard-linking, we were able to achieve stable convergence with a low tolerance of 10^{-5}. Earlier soft-linked full-link contributions have reported partial lack of convergence. Our hard-linking approach also exposed many convergence challenges. Initially we observed situations with multiple equilibria in the REMES model. These situations exposed model errors, which could otherwise easily go undetected. We have observed different kinds of cycling behavior during iterations, which we have been able to avoid by adjusting the model and the linking calculations. Our full-link full-form hard-linking avoids human judgment and error, ensures replicability and speeds up scenario testing tremendously. It also exposes iterative challenges like cycling behavior, permits stringent convergence requirements, and increases the likelihood of detecting any multiple equilibria.

We have demonstrated this methodology on a study of the relations between the transport sector, the energy system and the regional economy using the models REMES and TIMES, with a target of decreasing climate gas emissions by 50% from the Norwegian transport sector compared to 1990. The target is reached by making technology investments in hydrogen vehicles. The considerable technology investments consume capital and limit the capital stock growth, decreasing the value of total production in 2030 by 2.8%. The decrease in household welfare corresponds to a 6.5% salary reduction.

The linking provides model harmonization, producing results that are consistent across both the bottom-up and top-down model.[8] The linking is also essential for levelling out regional welfare reductions. There are large regional welfare differences during the first iterations, and it takes several linking iterations before the regional effects stabilize.

The energy system costs from technology investments depend heavily on the demand differences in the various scenarios. This observation indicates that it would be relevant to extend the analysis with alternative policy options directly affecting demand, for example transport taxes or fuel taxes.

A promising area for further research is to assess autonomous energy efficiency improvements in the top-down model based on results from the technology rich bottom-up model in the linking procedures. Changes in the energy mix may then lead to important income effects as well as substitution effects in the top-down model. Integration of these effects provide an interesting area for future research, and availability of hard-linked models will greatly improve our ability to do so.

Acknowledgements

This work was supported by the Norwegian Research Council project Regional effects of energy policy (216513), and by Enova SF.

The authors would like to thank Gerardo A. Perez-Valdes, Arne Stokka, Ulf Johansen, Lars Vik, Adrian Werner, Eva Rosenberg, Anna Krook-Riekkola, Pernille Seljom and Kari Espegren for their valuable comments and suggestions. We also thank user participants in the project for valuable feedback on preliminary findings.

Appendix

7.1. E3 and integrated assessment models

Top-down and bottom-up models in general belong to the broader class of energy-economy-environment (E3) models [17,50], together with integrated assessment models (IAM) [51] which also should be mentioned here as a hybrid model approach. A broad definition is that IAMs integrate knowledge from two or more domains into a single framework [52], but the typical aim is to combine the scientific and economic aspects of climate change in order to assess policy options for climate change [53]. IAMs usually consists of many hard-linked modules [54], not only bottom-up and top-down.

7.2. Nesting structure

Nesting structures are commonly grouped into KLEM branches, where KLEM stands for Capital, Labour, Energy and Materials [55]. The two major forms of substitution structures are the ((KE)L)M and the ((KL)E)M forms [56], see Fig. 15.

The nesting variants (KE)L, (KL)E and (EL)K are compared for the German industry in Kemfert [57] and Kemfert and Welsch [58]. The (KE)L nesting is chosen for the entire German industry, while (KL)E nesting is more realistic for most individual industrial sectors. All nesting structures are also systematically compared in van der Werf [55], who concludes that the (KL)E nesting structure fits the data best. The same (KL)E nesting structure is used in Koesler and Schymura [43]. Data from the World-Input-Output-Database (WIOD) is utilized to estimate a consistent dataset of substitution elasticities for the three-level nested KLEM production structure covering 35 industries. The elasticities are estimated by nonlinear estimation techniques. Relevant elasticities are compared with elasticities from van der Werf [55], Okagawa and Ban [56] and Kemfert [57].

We use elasticities reported in Koesler and Schymura [43], but we assume a Leontief nesting of the energy goods (substitution elasticities are assumed to be zero). Both the top-down and the bottom-up model assume a region- and sector specific production structure. The regional Leontief coefficients for energy goods are adjusted on the basis of regional energy quantities calculated in the bottom-up model TIMES.

7.3. Effect of capital linking in co2k

Energy system investments in TIMES are significantly higher in the CO_2 reduction scenarios than the *bau* scenario, as shown in Table 5. Total investment costs are EUR 177 million in the *bau* scenario, while investments increase to EUR 296 million in the *co2* scenario. This bottom-up increase in investments affects capital growth in the top-down model. REMES decreases demand and investments revert to EUR 275 million in the *co2k* scenario.

The regions have different base year levels of capital, and the investment needs from the bottom-up model shown in Fig. 16 have different regional damping effects on capital growth.

Fig. 17 shows regional capital growth adjustments in REMES due to investments in TIMES.

The East region has the largest capital base, and region South has the lowest growth of TIMES investments. Both regions have smaller decreases in capital growth than the other regions, as Fig. 17 shows. Regions Middle and West have similar capital bases, but TIMES investments are larger in the Middle region. This region has the largest drop in capital growth. We also see in Fig. 17 that this region has the largest fluctuations during the model linking iterations. Fig. 18 shows how the cost of capital depends on the capital stock growth adjustments. The cost of capital is low during the *bau* iterations, since the full capital stock growth is available in REMES. When capital is consumed for technical investments in TIMES, the cost of capital is affected inversely. In the next section we look at the regional welfare consequences.

7.4. Computer runtime

Computer runtime on a Dell Precision T7600 with two Intel Xeon CPU E5-2650 2 GHz processors are shown in Table 6.

7.5. Data mappings

Table 7 shows instructive examples of the data mappings.

Table 8 show complete mapping between energy commodities in TIMES and REMES.

Table 9 lists the sectors in REMES.

Table 10 lists the commodities in REMES.

---

[8] The supply of energy services from the bottom-up model is consistent with the demand in the top-down model, and the energy mix in the top-down model is consistent with the supply in the bottom-up model.

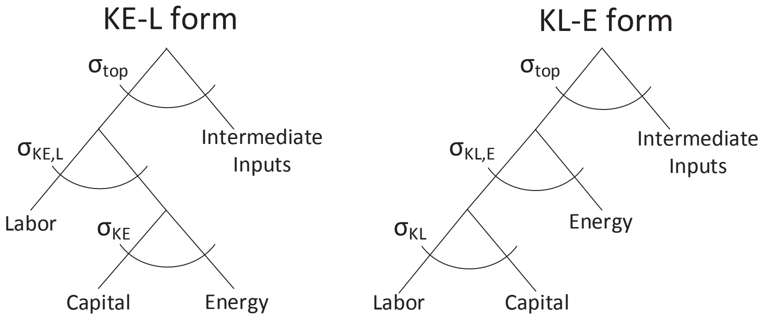

Fig. 15. Two major forms of substitution structures (see Okagawa and Ban [56] Fig. 2).

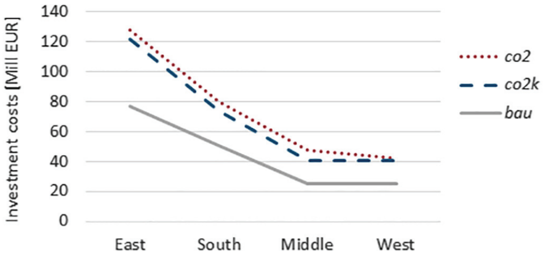

Fig. 16. Regional bottom-up investment costs per region by scenario.

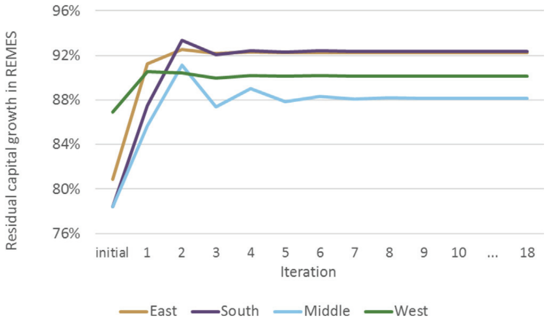

Fig. 17. Regional capital growth adjustments in REMES due to investments in TIMES (*co2k* scenario).

Fig. 18. Cost of capital per region for *bau* and *co2k* scenario.

Table 5
Regional investment costs in bottom-up model [million Euro].

	bau	*co2*	*co2k*	Increase from *bau* to *co2k*
East	76.6	127.4	121.1	58%
South	50.5	79.4	73.3	45%
Middle	25.0	47.2	40.4	62%
West	25.2	41.9	40.3	60%
Grand Total	**177.3**	**296.0**	**275.1**	**55%**

Table 6
Computer running times.

Scenario	Total run time	Top-down run time	Bottom-up run time	Top-down share	Bottom-up share	Iterations	Minutes per iteration
bau	2 h 52 m	0 h 06 m	2 h 46 m	3.5%	96.5%	6	29
co2	3 h 05 m	0 h 06 m	2 h 59 m	3.2%	96.8%	6	31
co2k	8 h 53 m	0 h 19 m	8 h 34 m	3.6%	96.4%	18	30

Table 7
Mapping of data structures.

id	Mapping	TIMES bottom-up (example)	REMES top-down (example)	Coef-ficient
a)	Regions $R_{r'}$ and R'_r TIMES regions towards REMES regions (5 mappings in total)	NO1	R1	n/a
		NO2	R2	n/a
		…	…	
b)	Energy commodities $C_{c'}$ and C'_c TIMES energy commodities mapped towards energy commodities in REMES. (50 mappings)	NG-L	c_NG	n/a
		NG-LPG	c_NG	n/a
		…	…	n/a
		BIO-PEL	c_BIO	
c)	Sectors TIMES→REMES $\mu_{p',s}$ TIMES processes (demand devices) mapped towards REMES sectors. (519 mappings)	CEDUH001 (oil boiler, education)	i-CEDU	100%
		CEDUH002 (natural gas boiler, education)	″	100%
		…	HOUS	85%
		TCART401-S (Gasoline car short distance)	i-TLND	15%
		“… TOTHT400 (Fuels for transport use - other mobile combustion)”	i-AAGR	67%
			i-CCON	33%
d)	Sectors REMES→TIMES $k_{s,s'}$ TIMES energy services in demand sectors mapped towards REMES sectors (83 mappings)	COFFE (electricity demand in commercial offices)	i-COFF	0.703
		COFFH (heating demand in commercial offices)	″	0.535
		…	HOUS	1.231
		TCART-S (Personal Cars Short Distance)	i-TLND	0.05
		“… TOTHT (Other mobile combustion)”	i-AAGR	1.0
			i-CCON	1.0

Table 8
Mapping of energy commodities.

TIMES commodity	TIMES description	REMES commodity	REMES description
ELC-HP	Electricity High Voltage: From unregulated hydro	c_POW	Electricity
ELC-HV	Electricty High Voltage	c_POW	Electricity
ELC-LV	Electricty Low Voltage	c_POW	Electricity
ELC-LV-LOSS	Electricity Low Voltage: Losses in grid	c_POW	Electricity
ELC-LV-LOSS-DEMAND	Demand for LV-losses in grid (dummy)	c_POW	Electricity
ELC-WP	Electricity High Voltage: From wind power	c_POW	Electricity
BIO-BAR	Bark	c_BIO	Bio-energy
BIO-BLI	Black liqour	c_BIO	Bio-energy
BIO-COAL	Bio-Coal	c_BIO	Bio-energy
BIO-COKE	Bio-Coke	c_BIO	Bio-energy
BIO-DSL	Biodiesel (2. gen)	c_BIO	Bio-energy
BIO-ETN	Ethanol (E85)	c_BIO	Bio-energy
BIO-FOR	Biomass from forrestry	c_BIO	Bio-energy
BIO-MWS	Municipal waste	c_BIO	Bio-energy
BIO-OILI	Syntetic biomass oil, industrial use	c_BIO	Bio-energy
BIO-OILS	Syntetic biomass oil, stationary use	c_BIO	Bio-energy
BIO-PEL	Pellets	c_BIO	Bio-energy
BIO-SAW	Biomass saw	c_BIO	Bio-energy
BIO-WDO	Wood	c_BIO	Bio-energy
COAL	Coal (COAL-HC & BIO-COAL)	c_COAL	Coal
COAL-COKE	Coke	c_COAL	Coal

(*continued on next page*)

Table 8 (*continued*)

TIMES commodity	TIMES description	REMES commodity	REMES description
COAL-HC	Hard coal	c_COAL	Coal
OIL-CRUDE	Crude oil	c_COIL_	Crude oil
LTH	District heating	c_LTH	District heating
LTH1	District heating to grid	c_LTH	District heating
LTH-ALA	LTH Aluminium A	c_LTH	District heating
LTH-ALR	LTH Aluminium R	c_LTH	District heating
LTH-EDU	LTH Education	c_LTH	District heating
LTH-HEA	LTH Health and social services	c_LTH	District heating
LTH-HOT	LTH Hotel and restaurant	c_LTH	District heating
LTH-MEA	LTH Metal industry A	c_LTH	District heating
LTH-MER	LTH Metal industry Rest	c_LTH	District heating
LTH-MUN	LTH Multi-family houses, new	c_LTH	District heating
LTH-MUO	LTH Multi-family houses, old	c_LTH	District heating
LTH-OFF	LTH Office buildings	c_LTH	District heating
LTH-OTH	LTH Service sector other	c_LTH	District heating
LTH-PPA	LTH Pulp and paper A	c_LTH	District heating
LTH-PPR	LTH Pulp and paper R	c_LTH	District heating
LTH-RES	LTH Rest industry	c_LTH	District heating
LTH-SIN	LTH Single family houses, new	c_LTH	District heating
LTH-SIO	LTH Single family houses- old	c_LTH	District heating
LTH-ST-RES	LTH Steam Turbine Rest industry	c_LTH	District heating
LTH-WSR	LTH Wholesale and Retail	c_LTH	District heating
LTH-ALB	LTH Aluminium B	c_LTH	District heating
LTH-ALC	LTH Aluminium C	c_LTH	District heating
NG-CNG	Compressed Natural Gas (CNG)	c_NG	Natural gas
NG-L	Natural gas before pipeline distribution (for indu	c_NG	Natural gas
NG-LPG	Liquid Petroleum Gas	c_NG	Natural gas
NG-PL	Natural gas after pipeline distribution (local)	c_NG	Natural gas
OIL-DSL	Diesel	c_OIL-DSL	Diesel
OIL-GSL	Gasoline	c_OIL-GSL	Gasoline
OIL-HDI	Heavy distillate for industry	c_OIL-HD	Heavy distillate
OIL-HDT	Heavy distillate for transport	c_OIL-HD	Heavy distillate
OIL-JET	Jet fuel	c_OIL-JET	Jet fuel
OIL-KER	Kerosene	c_OIL-KER	Kerosene
OIL-LDI	Light distillate, industrial use	c_OIL-LD	Light distillate
OIL-LDIF	Light distillate, industrial use (fossil)	c_OIL-LD	Light distillate
OIL-LDS	Light distillate, stationary use	c_OIL-LD	Light distillate
OIL-LDSF	Light distillate, stationary use (fossil)	c_OIL-LD	Light distillate
OIL-LDT	Light distillate for transport (marine diesel)	c_OIL-LD	Light distillate

Table 9
List of REMES sectors.

Sector	REMES description	Sector	REMES description
i-AAGR	Agriculture, forestry and fishing	i_COAL	Mining of coal and lignite
i-IMIN	Mining and oil exploitation	i_COIL	Extraction of crude oil
i-IRES	Rest industry	i_NG-GASE	Extraction of natural gas
i-IPPA	Paper and paper products	i_NG-GASL	Natural gas liquids
i-IMEA	Iron, steel and other metals	i_OIL-GSL	Gasoline
i-IREF	Refinery	i_OIL-JET	Jet fuel
i-ICHA	Chemicals	i_OIL-KER	Kerosene
i-IALA	Aluminium	i_OIL-DSL	Diesel
i-CCON	Construction and building	i_OIL-HD	Heavy distillate
i-CWSR	Wholesale and retail	i_NG	Refinery gas
i-CHOT	Hotel and restaurant	i_CRUDE-OIL	Refinery feedstocks
i-COFF	Office buildings	i_OIL-LD	Light distillate
i-CEDU	Education	i_POW	Electricity
i-CHEA	Health services	i_POWTD	Electricity transmission and distribution
i-COTH	Other commercial	i_LTH	Steam and hot water supply
i-TRAI	Transport via railways		
i-TLND	Other land transport		
i-TPIP	Transport via pipelines		
i-TSEA	Sea transport		
i-TAIR	Air transport		
i-Waste	Waste treatment		

Table 10
List of REMES commodities.

Commodity	REMES description	Commodity	REMES description
c-AAGR	Agriculture, forestry and fishing	c_BIO	Bio energy and hydrogen
c-IMIN	Mining and oil exploitation	c_COAL	Coal
c-IRES	Rest industry	c_COIL_	Crude oil
c-IPPA	Paper and paper products	c_NG	Natural gas
c-IMEA	Iron, steel and other metals	c_OIL-GSL	Gasoline
c-ICHA	Chemicals	c_OIL-JET	Jet fuel
c-COTH	Other commercial	c_OIL-KER	Kerosene
c-CCON	Construction and building	c_OIL-DSL	Diesel
c-CWSR	Wholesale and retail	c_OIL-HD	Heavy distillate
c-CHOT	Hotel and restaurant	c_OIL-LD	Light distillate
c-COFF	Office	c_POW	Electricity
c-CEDU	Education	c_POWTD	Electricity distribution
c-CHEA	Health services	c_LTH	Steam and hot water
c-TRAI	Transport via railways		
c-TLND	Other land transport		
c-TPIP	Transport via pipelines		
c-TSEA	Sea transport		
c-TAIR	Air transport		
c-Waste	Waste		

References

[1] Arrow KJ, Debreu G. Existence of an equilibrium for a competitive economy. Econometrica 1954;22(3):265–90.

[2] Johansen L. A multi-sector study of economic growth. Amsterdam, Netherlands: North-Holland Publishing Company; 1960.

[3] Dixon PB, Jorgenson DW. Handbook of computable general equilibrium modeling. North Holland; 2013.

[4] Böhringer C, Löschel A. Computable general equilibrium models for sustainability impact assessment: status quo and prospects. Ecol Econ 2006;60(1): 49–64.

[5] Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technologies and the cost of limiting US CO2 emissions. Energy Pol 2006;34(18):3847–69.

[6] Lanz B, Rausch S. General equilibrium, electricity generation technologies and the cost of carbon abatement: a structural sensitivity analysis. Energy Econ 2011;33(5):1035–47.

[7] Binswanger M. Technological progress and sustainable development: what about the rebound effect? Ecol Econ 2001;36(1):119–32.

[8] Grubb M, Edmonds J, ten Brink P, Morrison M. The costs of limiting fossil-fuel CO2 emissions: a survey and analysis. Annu Rev Energy Environ 1993;18: 397–478.

[9] Hourcade JC, Jaccard M, Bataille C, Ghersi F. Hybrid modeling: new answers to old challenges - introduction to the special issue of the Energy Journal. Energy J 2006:1–11.

[10] Böhringer C, Rutherford TF. Combining bottom-up and top-down. Energy Econ 2008;30(2):574–96.

[11] Wene CO. Energy-economy analysis: linking the macroeconomic and systems engineering approaches. Energy 1996;21(9):809–24.

[12] Böhringer C, Rutherford TF. Integrated assessment of energy policies: decomposing top-down and bottom-up. J Econ Dynam Contr 2009;33(9): 1648–61.

[13] Hoffman KC, Jorgenson DW. Economic and technological models for evaluation of energy-policy. Bell J Econ 1977;8(2):444–66.

[14] Drouet L, Haurie A, Labriet M, Thalmann P, Vielle M, Viguier L. A coupled bottom-up/top-down model for GHG abatement scenarios in the swiss housing sector. In: Loulou R, Waaub J-P, Zaccour G, editors. Energy and environment. US: Springer; 2005. p. 27–61.

[15] Schafer A, Jacoby HD. Experiments with a hybrid CGE-MARKAL model. Energy J 2006:171–7.

[16] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: lessons from linking a Swedish energy system model with a CGE model. Energy 2017;141:803–17.

[17] Fortes P, Pereira R, Pereira A, Seixas J. Integrated technological-economic modeling platform for energy and climate policy analysis. Energy 2014;73: 716–30.

[18] Manne AS. ETA-macro: a model of energy-economy interactions. Technical report. Palo Alto, California: Electric Power Research Institute; 1977.

[19] Strachan N, Kannan R. Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ 2008;30(6):2947–63.

[20] Messner S, Schrattenholzer L. Message-macro: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000;25(3):267–82.

[21] Kypreos S, Lehtila A. Decomposing Tiam-macro to assess climatic change mitigation. Environ Model Assess 2015;20(6):571–81.

[22] Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M. WITCH - a World induced technical change hybrid model. Energy J 2006:13–37.

[23] Duan H-B, Zhu L, Fan Y. Optimal carbon taxes in carbon-constrained China: a logistic-induced energy economic hybrid model. Energy 2014;69(Suppl. C): 345–56.

[24] Böhringer C. The synthesis of bottom-up and top-down in energy policy modeling. Energy Econ 1998;20(3):233–48.

[25] Scarf H, Hansen T. The computation of economic equilibria. Yale University: Yale University Press; 1973.

[26] Mathiesen L. Computation of economic equilibria by a sequence of linear complementarity-problems. Math Program Stud 1985;23(OCT):144–62.

[27] Böhringer C, Löschel A. Promoting renewable energy in Europe: a hybrid computable general equilibrium approach. Energy J 2006:135–50.

[28] Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Econ 2008;30(2):547–73.

[29] Proença S, St Aubyn M. Hybrid modeling to support energy-climate policy: effects of feed-in tariffs to promote renewable energy in Portugal. Energy Econ 2013;38(0):176–85.

[30] Rausch S, Mowers M. Distributional and efficiency impacts of clean and renewable energy standards for electricity. Resour Energy Econ 2014;36(2): 556–85.

[31] Abrell J, Rausch S. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. J Environ Econ Manage 2016;79: 87–113.

[32] NTP. National transport plan 2018-2029 (basis document, English summary). Oslo, Norway: Norwegian national rail administration, Norwegian coastal administration, Norwegian public roads administration and Norwegian air traffic authority (Avinor). 2016. p. 14.

[33] ETSAP. The Energy Technology Systems Analysis Program, http://www.iea-etsap.org, accessed 2017-04-18.

[34] Lind A, Rosenberg E. How do various risk factors influence the Green certificate market of Norway and Sweden? Energy Proc 2014;58:6.

[35] Lind A, Rosenberg E, Seljom P, Fidje A, Lindberg K. Analysis of the EU renewable energy directive by a techno-economic optimisation model. Energy Pol 2013;60:13.

[36] Statnett. Elspot areas, http://www.statnett.no/en/Market-and-operations/the-power-market/Elspot-areas–historical/Elspot-areas/, accessed 2017-04-18.

[37] Rosenberg E, Lind A, Espegren KA. The impact of future energy demand on renewable energy production - case of Norway. Energy 2013;61:419–31.

[38] Werner A, Perez-Valdes GA, Johansen U, Stokka AM. REMES - a regional equilibrium model for Norway with focus on the energy system. SINTEF Technology and Society; 2017.

[39] Ivanova O, Vold A, Jean-Hansen V. PINGO - a model for prediction of regional- and interregional freight transport. Institute of Transport Economics (TØI); 2002. p. 48.

[40] Ivanova O, Heyndrickx C, Spitaels K, Tavasszy L, Manshanden W, Snelder M, et al. RAEM: version 3.0. Transport & mobility Leuven. 2007. p. 77.

[41] Brandsma A, Kancs D. RHOMOLO: a dynamic general equilibrium modelling approach to the evaluation of the European Union's R&D policies. Reg Stud 2015;49(8):1340–59.

[42] Armington PS. A theory of demand for products distinguished by place of production. Int Monetary Fund Staff Pap 1969;16(1):159–78.

[43] Koesler S, Schymura M. Substitution elasticities in a CES production framework. Discussion Paper No 12–1007. ZEW - Centre for European Economic Research; 2012.

[44] Garcia-Gusano D, Espegren K, Lind A, Kirkengen M. The role of the discount rates in energy systems optimisation models. Renew Sustain Energy Rev

2016;59:56–72.
[45] Bjerkan KY, Nørbech TE, Nordtømme ME. Incentives for promoting Battery electric vehicle (BEV) adoption in Norway. Transport Res Transport Environ 2016;43:169–80.
[46] Figenbaum E, Assum T, Kolbenstvedt M. Electromobility in Norway: experiences and opportunities. Res Transport Econ 2015;50:29–38.
[47] Rosenberg E, Espegren K, Holden E, Wicken O, Ryghaug M, Sørensen KH. Energy demand projections towards 2050-Reference path. Centre for Sustainable Energy Studies (CenSES); 2015. p. 36.
[48] Shoven JB, Whalley J. Applied general-equilibrium models of taxation and international trade: an introduction and survey. J Econ Lit 1984;22(3):1007–51.
[49] Dakhlia S. Testing for a unique equilibrium in applied general equilibrium models. J Econ Dynam Contr 1999;23(9–10):1281–97.
[50] Ghersi F. Hybrid bottom-up/top-down energy and economy outlooks: a review of IMACLIM-S experiments. Front Environ Sci 2015;3(74).
[51] Löschel A. Technological change in economic models of environmental policy: a survey. Ecol Econ 2002;43(2–3):105–26.
[52] Weyant J, Davidson O, Dowlatabadi H, Edmonds J, Grubb M, Parson E, et al. Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce JP, Lee H, Haites EF, editors. Climate change 1995: economic and social dimensions of climate change. Cambridge: Cambridge University Press; 1996. p. 367–439.
[53] Kelly DL, Kolstad CH. Integrated assessment models for climate change control. In: Folmer H, Tietenberg T, editors. International yearbook of environmental and resource economics 1999/2000; a survey of current issues. Cheltenham: Edward Elgar Publishing; 1999.
[54] Parson EA, FisherVanden K. Integrated assessment models of global climate change. Annu Rev Energy Environ 1997;22:589–628.
[55] van der Werf E. Production functions for climate policy modeling: an empirical analysis. Energy Econ 2008;30(6):2964–79.
[56] Okagawa A, Ban K. Estimation of substitution elasticities for CGE models. Discussion papers in economics and business, No 08-16. 2008. Osaka.
[57] Kemfert C. Estimated substitution elasticities of a nested CES production function approach for Germany. Energy Econ 1998;20(3):249–64.
[58] Kemfert C, Welsch H. Energy-capital-labor substitution and the economic effects of CO2 abatement: Evidence for Germany. J Pol Model 2000;22(6):641–60.

Paper IV

From linking to integration of energy system models and computational general equilibrium models – effects on equilibria and convergence

Paper IV

Energy 159 (2018) 1218–1233

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

From linking to integration of energy system models and computational general equilibrium models – Effects on equilibria and convergence

Per Ivar Helgesen[*], Asgeir Tomasgard

Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Norway

ARTICLE INFO

Article history:
Received 29 October 2017
Received in revised form
15 April 2018
Accepted 21 June 2018
Available online 22 June 2018

Keywords:
Hybrid modeling
Energy system analysis
Economic modeling
Model linking
Integrated models
Stackelberg equilibrium

ABSTRACT

This paper compares hard-linked and integrated approaches of hybrid top-down and bottom-up models in terms of equilibria and convergence. Four setups where a bottom-up linear programming model is hard-linked with a top-down computable general equilibrium model are implemented. A solution is found by iterating between the two models, until convergence is reached. The same equilibrium solution is found by all hard-linked setups in all problem instances. Next, one integrated model is introduced by extending the computable general equilibrium mixed complementarity model with the Karush-Kuhn-Tucker conditions that represent the bottom-up linear programming model. This integrated model provides the same solutions as the hard-linked models. Also, an alternative integrated model is provided, where the bottom-up model objective is optimized while the top-down model is included as additional constraints. This nonlinear program corresponds to a multi-follower bilevel formulation, with the energy system model as the leader and the general equilibrium players (firms and household) as followers. The Stackelberg equilibrium from this bilevel formulation pareto-dominates the Nash equilibrium from the other model setups in some problem instances, and is identical in the remaining problem instances. Different ways to couple the mathematical models may result in different solutions, because the coupling represents different real-world situations.

1. Introduction

A challenge in modeling energy policy is to capture energy system effects, impact on the general economy and feedback effects in an adequate way. Different approaches to combine economic modeling with energy system modeling exist in the literature. This paper compares hard-linking approaches with hybrid models implementing full integration of a top-down economy model and a bottom-up energy system model. Top-down and bottom-up models represent two contrasting and wide-spread approaches for quantitative assessment of energy policies [1]. The strengths of one model complement the other model. Grubb et al. described early how economic models assume that no investments are available beyond the production frontier, while engineering models assume widespread potential for investments beyond this frontier [2]. Wene [3] discusses how the two approaches differ in their identification of the relevant system, and thus complement each other, while Böhringer and Rutherford [4] employ the complementarity format to combine the technological explicitness of bottom-up models with the economic comprehensiveness of top-down models.

Our contribution is to compare different ways of combining top-down and bottom-up models using both complementarity formulations and optimization formulations as well as hard linking and full integration. The main contribution is to integrate full-linked hybrid models and compare with hard-linked approaches. The authors are not aware of previous work that investigates this comparison.

Bottom-up engineering models include thorough descriptions of technological aspects of the energy system, including future improvements. They include interactions among the numerous individual energy technologies that make up the energy system of an economy, from primary energy sources, via conversion and distribution processes to final energy use. A solution constitutes a partial equilibrium where energy demand is fulfilled in a cost-

---

[*] Corresponding author.
E-mail addresses: per.ivar.helgesen@ntnu.no (P.I. Helgesen), asgeir.tomasgard@ntnu.no (A. Tomasgard).

https://doi.org/10.1016/j.energy.2018.06.146

optimal fashion. Bottom-up models neglect the macroeconomic impact of energy policies, since they are partial equilibrium models and look only at the energy market. They are also unable to capture the full economy-wide rebound effects. They can easily capture substitution of energy carriers or technologies, but cannot anticipate demand adjustments due to income effects [5].

Top-down computable general equilibrium (CGE) models, on the other hand, describe the whole economy, and emphasize the possibilities to substitute different production factors in order to maximize the profits of firms. The substitution possibilities between energy and other production factors are captured in production functions, which describe changes in fuel mixes as the result of price changes under certain substitution elasticities. Prices are determined by the market clearance conditions that equalize supply and demand for all commodities in the economy, both energy and non-energy alike. The main workhorse in CGE modeling is the constant elasticity of substitution (CES) function. This function generalizes the Leontief function and the Cobb-Douglas function, and is used to model production, consumer utility and trade, usually in nested hierarchies [6]. One challenge is that such production functions can result in violation of basic energy conservation principles. The CES function aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy flows [7]. Top-down representations of technologies can also produce fuel substitution patterns that are inconsistent with bottom-up cost data [8].

While bottom-up models usually emerge from linear programming (LP), CGE models are typically formulated as mixed complementarity problems (MCP), based on the framework of Mathiesen [9]. This modeling exploits the complementarity features of economic equilibrium: 1) Each activity that runs must reach zero profit. If the profit is negative, it will not run. 2) Each good must have a price that clears the market (demand equals supply). The good can be oversupplied only if the price is zero. 3) Consumer utility is assumed to be insatiable, thus every household will spend all its income (the model may include opportunities to save income for future consumption). CGE models are highly nonlinear, and may have more than one solution. Known conditions that are sufficient for uniqueness are highly restrictive. If either the weak axiom of revealed preference (WARP) or gross substitutability (GS) is satisfied by the consumer excess demand function, then a pure exchange economy has a unique equilibrium [10]. For CGE models involving production, Mas-Colell [11] provides sufficient conditions for uniqueness by proving that economies with CES utility and production functions whose elasticities of substitution are greater than or equal to one are guaranteed to have a unique equilibrium in the absence of taxes and other distortions. These conditions are restrictive, and introduction of taxes further complicates formulation of sufficient conditions for uniqueness [12].

There are few examples of models with multiple equilibria. Kehoe provides an overview with numerical examples [12]. According to Dierker [13], the number of equilibria in exchange economies is odd. Whalley and Zhang show tax-induced examples with 3 equilibria in a 2-individual 2-good pure exchange economy [14], and they are able to find 5 equilibria in a 3-individual 2-good pure exchange economy [15]. There are also examples of multiple equilibria in CGE models with production and increasing returns. Mercenier [16] reports two equilibria in a large-scale applied world economy CGE model. Denny et al. [17] find two equilibria while studying tax reforms using a CGE covering the Irish economy. The possibility of multiple equilibria means that convergence of solution algorithms cannot be guaranteed [18]. Mathiesen [19] discusses why theoretical results concerning convergence are few, but for a specific example with linear complementarity problems he is able to proof convergence if one solution exists. The possibility of multiple equilibria prohibits us from studying alternative decomposition methods for the integrated models that relies on convexity, for example Benders decomposition.

Hybrid models aim to combine the technological explicitness of bottom-up models with the economic richness of top-down models [4]. This can be accomplished in different fashions. Wene classifies model linking as (informal) *soft-linking* versus (formal) *hard-linking* [3]. Böhringer and Rutherford [18] do not use the term “hard-linking”, but define three categories: 1) Coupling of existing large-scale models, 2) having one main model complemented with a reduced form representation of the other, and 3) directly combining the models as mixed complementarity problems. This paper adopts the terms *soft-linking* and *hard-linking* as defined by Wene [3], where soft-linking is information transfer controlled by the user and hard-linking is formal links where information is transferred by computer programs without any user judgment. One further step is to *integrate* the models, as in the third category of Böhringer and Rutherford [18]. Integrated models are run as one, instead of exchanging information between separate model runs. Fig. 1 depicts these variants of hybrid modeling.

Fortes et al. [20] use the terms “full-link” and “full-form” to characterize hybrid models. Full-link hybrid models cover all economic sectors, while full-form hybrid models combine detailed and extensive technology data with disaggregated economic structure. Despite the extensive literature on hybrid models, there are few quantitative examples employing full-link and full-form bottom-up and top-down approaches [20].

Soft-linking is the natural way to start, when large-scale standalone models already have been implemented. Early examples are found in Hoffman and Jorgenson [21], who couple an econometric macroeconomic model with a process analysis model of the energy sector, Hogan and Weyant [22], who define a model framework and a solution method which moves through a network of process models, and Messner and Strubegger [23], who combine an energy system model with an economic model consisting of five modules which are solved iteratively. Many contributions focus on specific sectors, for example soft-linking ETEM and GEMINI-E3 focusing on residentials [24] and soft-linking MARKAL and EPPA focusing on transport [25]. Recent examples employ full-link of all economic sectors, for example between TIMES and EMEC [26] and between TIMES and GEM-E3 [20].

Hard-linking has historically been accomplished by narrowing

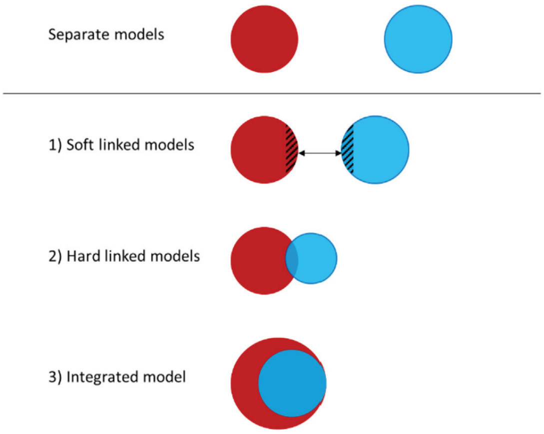

Fig. 1. Hybrid model variants.

the focus in one of the models, usually by aggregating the sectors of the economy. Examples are the ETA-Macro model [27], the MESSAGE-Macro model [28], and MARKAL-Macro (described methodologically by Manne and Wene [29], assessing inter-regional trade of CO_2 emissions [30], and studying long-term carbon reduction scenarios [31]). A recent example is provided by Arndt et al. [32], where the South African TIMES energy system model (SATIM) has been hard-linked to a detailed dynamic CGE model of South Africa (SAGE). However, the information interchange is related to electricity, and does not reflect the full sectoral coverage of the models.

Integration of bottom-up activity analysis into top-down CGE models was demonstrated in a static three-sector two-household sample model by Böhringer [33]. A dynamic extension was given by Frei [34], and a large-scale application was illustrated by Böhringer and Löschel, investigating renewable energy promotion in Europe [35]. The approach was extended by Böhringer and Rutherford [4], and further developed by adding a decomposition approach [18]. The conceptual idea was presented early by Scarf and Hansen [36] in 1973 (page 98), and further demonstrated by Mathiesen [9]. Such integrated hybrid models have focused on one selected sector, to maintain tractability. Most contributions in this category have focused on electricity. Sue Wing describes electric power technology detail in a social accounting framework [37], and studies the cost of limiting CO_2 emissions through carbon taxes [7]. Lanz et al. [8] presents a sensitivity analysis to demonstrate the pitfalls of making simplifying assumptions regarding emission abatement from the electricity sector. Their benchmark model utilizes the decomposition method described by Böhringer and Rutherford [18]. Proença and Aubyn assess feed-in tariffs for the promotion of electricity from renewable sources using a static CGE model of Portugal with integrated representation of the electricity sector [38]. Rausch and Mowers examine energy standards versus carbon pricing in five US policy scenarios toward the electricity sector [39]. Abrell and Rausch extends a multi-country multi-sector general equilibrium model with a bottom-up electricity dispatch model, to include electricity transmission infrastructure expansion [40].

This paper is oriented towards methodology, not policy analysis. The aim is to compare hard-linking and integration. However, in contrast to the integration approaches described previously, full detail is maintained in each model. It is assumed a setting where top-down and bottom-up models already have been implemented separately, and it is desirable to build on existing expertise without developing new models from scratch. This is a realistic starting point in many countries.

The scope has similarities to one previous study by Bauer, Edenhofer and Kypreos [41], which also compares linking of separate models with an integrated model approach.[1] Instead of a top-down CGE model, they consider a Ramsey-type macroeconomic growth model. They conclude that linking the models does not guarantee simultaneous equilibrium at the energy and capital market. A sound coupling requires integrating the models, and solving one very complex non-linear programming problem. Furthermore, integrating the models limits the level of detail and complexity of the energy system model.

Our approach to integration maintains full detail in each model. However, we simplify the representation of the time dimension, and use a static CGE model. We implement various versions of hard-linking and novel approaches to integration, using a stylized bottom-up TIMES model and a static top-down CGE model. One of the described hard-link approaches has been implemented on large-scale stand-alone models, employing a full-link and full-form bottom-up and top-down approach. A policy study based on this implementation is provided in Helgesen et al. [42].

All model reformulations are implemented without any need to change data inputs to the respective models. Demand for energy services are derived from equilibrium solutions of the CGE model, and employed as exogenous input to the bottom-up model. Solutions from the bottom-up TIMES model are then used to adjust the input-output structure describing future energy use in the different economic sectors of the CGE. This is an alternative approach to the CES functions that are routinely used in long term economic models. CES functions are central building blocks of General Equilibrium Integrated Assessment Models, which run future scenarios until year 2100 - for example in the Assessment Reports from the Intergovernmental Panel on Climate Change (IPCC). However, the focus in these reports has shifted from a single-discipline cost-benefit analysis to multi-disciplinary uncertainty analyses [43], as the economic models have important weaknesses. They cannot foresee actions that are profitable but not implemented (for example the energy “efficiency gap” [44]), and technological progress is often modelled as “manna from heaven” in the form of autonomous energy efficient improvement factors [45]. Kaya, Csala and Sgouridis [46] present critical views towards CES functions, claiming that this practice fails to match historically observed patterns in energy transition dynamics and that results are sensitive to parameter choices and the nesting. CES functions tend toward factor share preservation. The authors propose perfect substitution for alternative energy options, physical modeling complementing the economic analysis or applying functions with dynamic elasticity of substitution.

The approach in our paper improves upon the use of CES production functions in the energy sector, by utilizing the physical modeling of the energy system model as suggested [46]. Leontief production technologies with fixed input factors for energy inputs are assumed in the top-down CGE model, and Leontief coefficients are updated based on the bottom-up energy system model.[2]

Research questions for this paper are summarized as follows:

1) How can we integrate stand-alone versions of a top-down economic and a bottom-up energy system model?
2) Will hard-linked and integrated hybrid models produce the same solutions?
3) Will one larger, more complex integrated model be able to run in a similar time scale as two smaller separate hard-linked models?

The results presented are produced from stylized models, but the approach is generic and may be applied to large-scale models, as shown in Helgesen et al. [42]. The authors are not aware of any previous work that compares different implementations of full-linked integrated hybrid models.

The paper proceeds as follows. Our two models are presented in section 2, as well as the two hybrid modeling approaches. Section 3 presents results, demonstrating the interplay between models and comparing results from our hybrid model alternatives. The findings are discussed in section 4, and section 5 concludes the paper.

2. Methods

The purpose of this chapter is to define our mathematical

---

[1] Bauer et al. [41] define soft-link and hard-link differently from Wene [3], whose definitions we have applied in this paper.

[2] Income elasticities and elasticities of substitution are kept constant, as this is standard practice in CGE modeling, and the current models have no relevant basis for updating the elasticities endogenously.

models and the different hybrid variants we compare. The mathematical programming models of the energy system and of the whole economy are stylized, but general. Firms in the economy optimize their decisions in order to maximize profits, while other actors (for example government or households) similarly maximize their utility. The energy system supplies energy services to fulfil energy demand at the least cost attainable.

A static computable general equilibrium model describes a future economic equilibrium based on expected capital and labor growth. The energy system model calculates the optimal investments to meet the demands for energy services in this future economy. The resulting energy mix from the energy system model is used to update the computable general equilibrium model, resulting in new energy service demands.

This logic is first implemented using hard-linking, automatically iterating between both models until convergence is reached. Next, an integrated model is implemented, where the bottom-up model is represented by its Karush-Kuhn-Tucker conditions. Third, a different variant of the integrated model is implemented, where both models are integrated into one non-linear model.

Integrated models are solved either as a mixed nonlinear complementarity problem (MNCP) or as a nonlinear program (NLP). These variants are justified, since a nonlinear complementarity problem may equivalently be stated as a nonlinear program [47]. We exemplify this here by stating the pure nonlinear complementarity problem in vector form [48]. Given a vector-valued function *F(x)* defined for $x \geq 0$, find a solution that satisfies:

$$F(x) \geq 0, x \geq 0, F(x)^T x = 0 \tag{1}$$

This is often written more compactly as $0 \leq F(x) \perp x \geq 0$ with the perpendicular operator $\perp$ denoting the inner product of two vectors equal to zero. We may now state the nonlinear complementarity problem as a nonlinear program:

$$\min_x F(x)^T x \text{ subject to } F(x) \geq 0, x \geq 0 \tag{2}$$

Any feasible vector x satisfying the two non-negativity conditions must have $F(x)^T x \geq 0$. If there exists a solution satisfying the complementarity condition $F(x)^T x = 0$, it will also be a global minimizer of the nonlinear program. Given the existence of a solution to the complementarity problem, a global minimizer of the nonlinear program will also be a solution to the complementarity problem.

Typical examples of functions *F(x)* are zero profit conditions on production of goods, and market clearing conditions with regards to prices. A firm will not produce a good *x* if it earns a loss, production must reach zero profit (after paying wages and capital return). Similarly, a supplier will not experience a positive market price on a good in excess supply. A positive price implies market balance between supply and demand.

The models presented are scaled down, and many important real-world aspects or policy issues have been simplified, allowing us to focus on the linking and integration techniques. Nevertheless, the top-down and bottom-up models are general enough to represent large-scale, real world models, and the simplifications do not affect the validity of the analyses that are presented.

2.1. Bottom-up energy system model

Our bottom-up model has been defined and extracted from the TIMES (**T**he **I**ntegrated **M**arkal **E**fom **S**ystem) model generator, which has been developed in the frame of the implementing agreement IEA ETSAP.[3] A TIMES model gives a detailed description of the entire energy system including all resources, energy production technologies, energy carriers, demand devices, and sectorial demand for energy services. The model assumes perfect competition and perfect foresight (can also be used in a myopic mode) and is demand driven. The model finds the cost-minimizing way to fulfil energy service demands over a defined planning period. Yearly demands for heat and electricity are provided exogenously. Our stylized problem structure is depicted in Fig. 2.

Four technologies are available. Electricity can be produced from gaspower or hydropower. Heat can be produced by a gasburner or from electric heating. Only one region, one currency and a yearly timeslice are defined. For simplicity, a discount rate equal to zero is assumed, and discounting is omitted from the formulas.
The mathematical model is defined as follows:

Sets	
T	Time periods in bottom-up model, indexed by t (time) and v (vintage).
P	Processes in bottom-up model, indexed by p. This set includes the subset of production processes P_{prod} (as opposed to supply and demand processes). This set also includes subsets P_c^{in} (processes with commodity c as input) and P_c^{out} (processes with commodity c as output).
C	Commodities in bottom-up model, indexed by c. This set is further divided into natural supplied commodities C_{supply} and produced commodities C_{prod}.
Parameters	
$C_{t,p}^{cap}$	Capacity investment cost in year t and process p.
$C_{t,p}^{fom}$	Fixed operating and maintenance costs in year t for process p.
$C_{t,p}^{act}$	Activity cost in year t for process p.
$C_{t,c}^{prd}$	Production cost in year t for commodity c.
A_p^f	Availability factor[4] for process p.
α_p^{capact}	Capacity factor[4] in process p.
$\phi_{p,c,c'}$	Flow conversion factor in process p from commodity c to c'.
$D_{t,c}$	Demand in year t for commodity c.
$I_{2015,p}^{cap}$	Existing capacity in base year (2015) for process p.
$U_{t,p}^{cap}$	Upper bound on capacity investment in year t for process p.
$salvage_{t,p}$	Salvage value in horizon year (2026) from investment in year t in process p.
L_p	Technical lifetime (number of years) on investment in process p.
$\rho_{t,p}$	Remaining share of capacity from base year ($I_{2015,p}^{cap}$) in year t of process p.
Variables	
$i_{t,p}^{cap}$	Capacity investment in year t in process p.
$x_{t,p}^{act}$	Activity in year t in process p.
$x_{t,c}^{prd}$	Production in year t of commodity c.

Minimize system costs:

---

[3] The Energy Technology System Analysis Program of the International Energy Agency.

[4] The availability factor and capacity factor could be collapsed into a single parameter in this model, but these parameters are defined individually to maintain the correspondence to: the TIMES formulation.

$$\min_{i^{cap}_{t,p}, x^{act}_{t,p}, x^{prd}_{t,c}} \left(\begin{array}{l} \sum_{t=2015}^{2026} \sum_{p \in P} (1 - salvage_{t,p}) \left(C^{cap}_{t,p} \bullet i^{cap}_{t,p} \right) \\ + \sum_{v=2015}^{2026} \sum_{p \in P} \sum_{t=v}^{\min(2026, v+L_p-1)} C^{fom}_{t,p} \bullet i^{cap}_{v,p} + \sum_{t=2015}^{2026} \sum_{p \in P} C^{act}_{t,p} \bullet x^{act}_{t,p} + \sum_{t=2015}^{2026} \sum_{c \in C} C^{prd}_{t,c} \bullet x^{prd}_{t,c} \end{array} \right) \tag{3}$$

subject to
CAPACT: Process activity $\leq$ capacity

$$x^{act}_{t,p} \leq \sum_{v=\max(2015, t-L_p+1)}^{t} A^f_p \cdot \alpha^{capact}_p \cdot i^{cap}_{v,p} + A^f_p \cdot \alpha^{capact}_p \cdot \rho_{t,p} \cdot I^{cap}_{2015,p} \quad , \forall t \in [2015, 2026], p \in P_{prod} \tag{4}$$

COMBAL: Use of commodity $\leq$ commodity supply

$$D_{t,c} + \sum_{p \in P^{in}_c, c' \varepsilon C} \frac{x^{act}_{t,p}}{\phi_{p,c,c'}} \leq \sum_{p \in P^{out}_c} x^{act}_{t,p}, \quad \forall t \in [2015, 2026], \; c \in C \backslash C_{supply} \tag{5}$$

COMPRD: Commodity production must equal corresponding process activity

$$x^{prd}_{t,c} = \sum_{p \in P^{out}_c} x^{act}_{t,p} \quad , \forall t \in [2015, 2026] \quad , c \in C_{prod} \tag{6}$$

CAPUP: Capacity upper bounds

$$i^{cap}_{t,p} \leq U^{cap}_{t,p} \quad \forall t \in [2015, 2026] \quad , p \in P_{prod} \tag{7}$$

The modeling described above makes simplifying assumptions such as: 1) invested capacities are maintained (not depreciated) during their technical life, 2) economical lifetimes different from technical lifetimes are not considered, 3) vintages are not considered, and 4) early retirement is not considered.

2.2. Top-down computable general equilibrium model

A closed economy with production and competitive behavior throughout the economy is considered. A simple nesting structure is employed, where capital and labor are combined using a constant elasticity of substitution (CES) production function. The capital-labor composite is further combined with intermediate goods, using a Leontief production function (see Fig. 3).

In general, the economy is characterized by m firms, producing n goods to h households owning f factors. The stylized economy consists of four firms (or sectors) and one representative household. Each of the firms is producing one good. These goods are gas, electricity (ele), manufacturing (man) and non-manufacturing (non) respectively. The household owns two production factors: labor and capital. The behavior of the agents is modelled based on preferences, technology and budget constraints. The firms are assumed to maximize their profits, due to their production technology and their use of available production factors. The household is assumed to be maximizing its utility by spending its budget earned from its production factors. A Stone-Geary utility function is assumed, which gives rise to a linear expenditure system (a description is provided by Goldberger and Gamaletsos [49] page 364, see Lluch [50] for further references). The economic transactions from the base year are described in a social accounting matrix (SAM), which is shown in Table 1.

To simplify our hybrid implementations and improve readability, we assume positive prices for all goods and factors, and we assume that all four firms are producing in the equilibrium solution (as is the case in the base year). We formulate the CGE as a primal mathematical program, and define our equations with equal signs, instead of oriented inequalities. This allows us, without loss of generality, to simplify the NLP formulation and run the same code in NLP and MCP model setups. The mathematical model is defined as:

Sets	
I	Sectors in top-down model, indexed by i and j.
Parameters	
KS	Capital endowment (given in the SAM).
LS	Labor endowment (given in the SAM).
$io_{i,j}$	Input-output coefficient, amount input of good i to produce one unit of good j (calculated from the SAM).
σ^F_i	Constant elasticity of substitution (CES) between capital and labor in firm i.
γ^F_i	Distribution factor in CES production function of firm i.
a^F_i	Efficiency parameter in CES production function of firm i.
σ^h_i	Income elasticity of demand for good i.
α^h_i	Household marginal budget share of good i, sum over i equals one.
μ^h_i	Household subsistence level of good i.
Variables	
p_l	Price of labor (wage rate) (normalized to one in the base year).
p_k	Price of capital (return to capital) (normalized to one in the base year).
p_i	Price of good i (normalized to one in the base year).
x_i	Production of good i.
h	Household income.
L_i	Use of labor in sector i.
K_i	Use of capital in sector i.
c_i	Consumption of good i.

Zero profit conditions ($\perp x_i$):

$$p_i \cdot x_i = p_l \cdot L_i + p_k \cdot K_i + \sum_{j \in I} io_{j,i} \cdot p_j \cdot x_i \quad , \forall i \in I \tag{8}$$

Market clearing conditions for goods ($\perp p_i$):

$$c_i + \sum_{j \in I} io_{i,j} \cdot x_j = x_i \quad , \forall i \in I \tag{9}$$

Market clearing condition for production factor labor ($\perp p_l$):

$$\sum_{i \in I} L_i = LS \tag{10}$$

Market clearing condition for production factor capital ($\perp p_k$):

$$\sum_{i \in I} K_i = KS \tag{11}$$

Income balance ($\perp h$):

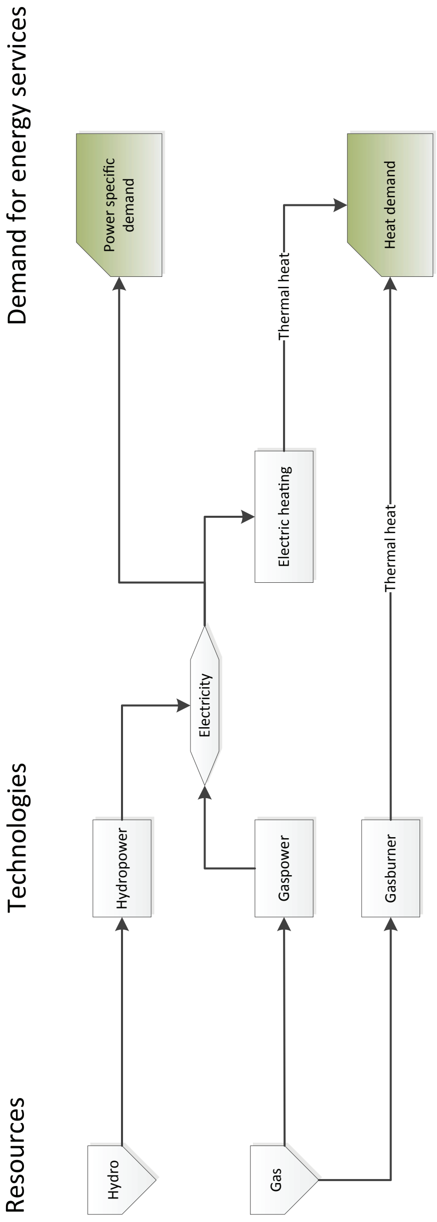

Fig. 2. Structure of the bottom-up model.

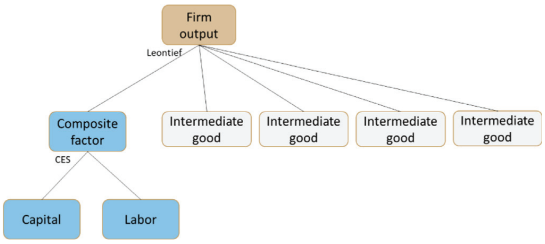

Fig. 3. Nesting structure.

Table 1
Social accounting matrix (SAM).

	gas	ele	man	non	L	K	hou	Tot
gas		4	2	3			1	*10*
ele	1	1	7	8			5	*22*
man	1	3	6	26			2	*38*
non	5	10	10	30			92	*147*
L	1	1	5	53				*60*
K	2	3	8	27				*40*
hou					60	40		*100*
Tot	*10*	*22*	*38*	*147*	*60*	*40*	*100*	

$$h = p_k \cdot KS + p_l \cdot LS \tag{12}$$

Household consumption $(\perp c_i)$:

$$p_i \cdot c_i = p_i \cdot \mu_i^h + \alpha_i^h \cdot \left(h - \sum_{j \in I} p_j \cdot \mu_j^h \right) \quad , \forall i \in I \tag{13}$$

Firm's use of labor solved explicitly $(\perp L_i)$:

$$L_i = \frac{x_i}{a_i^F} \cdot \left(\frac{1 - \gamma_i^F}{p_l} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k^{\left(1-\sigma_i^F\right)} + \left(1 - \gamma_i^F\right)^{\sigma_i^F} \cdot p_l^{\left(1-\sigma_i^F\right)} \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)} , \quad \forall i \in I \tag{14}$$

Firm's use of capital solved explicitly $(\perp K_i)$:

$$K_i = \frac{x_i}{a_i^F} \cdot \left(\frac{\gamma_i^F}{p_k} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k^{\left(1-\sigma_i^F\right)} + \left(1 - \gamma_i^F\right)^{\sigma_i^F} \cdot p_l^{\left(1-\sigma_i^F\right)} \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)} , \quad \forall i \in I \tag{15}$$

This system is homogenous of degree zero in prices. By Walras's law, one of the equations, against the same number of endogenous variables, is redundant [51]. A consequence is that absolute prices cannot be determined, and all prices are expressed relative to a chosen numeraire. The price of labor p_l is defined as numeraire, and the value is fixed to 1. In the base year, all prices are assumed to be equal to unity.

The modeling makes simplifying assumptions such as: 1) capital and labor are mobile among sectors and exogenously fixed, 2) there are no savings and investments, 3) there is no government, 4) the economy is closed, and 5) the model is static.

2.3. Links between the models

Fig. 4 shows the conceptual coupling between the top-down and bottom-up models. The top-down model calculates a future equilibrium based on exogenous changes (economic shocks), and the

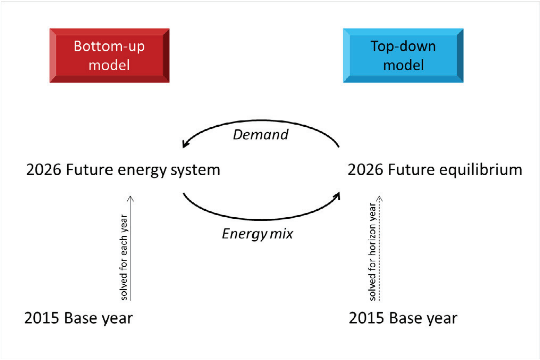

Fig. 4. Model coupling.

future economic equilibrium decides the demand for energy services in the horizon year of the bottom-up model. The static CGE model only calculates the horizon year equilibrium, and we assume for simplicity that demand develops linearly from the base year. A dynamic CGE model would provide demand also in intermediate years. The bottom-up energy system model then calculates the most cost-effective way to supply these energy services. The updated future energy mix is then taken into account by adjusting the input-output structure of the future economic equilibrium.

The bottom-up parameter $D_{t,c}$ for heat and electricity specific demand is calculated from the top-down model:

$$D_{t,c} = D_{2016,c} + D_{2016,c} \cdot \frac{x_{gas} + x_{ele} - x^0_{gas} - x^0_{ele}}{x^0_{gas} + x^0_{ele}} \cdot \frac{(t-2016)}{(2026-2016)}, \quad \forall t \in [2017, 2026], c \in \{electricitydemand, heatdemand\} \tag{16}$$

There is no direct correspondence (one to one relationship) between demand for energy services in the bottom-up model and the energy commodities in the top-down model. Increased use of gas in the top-down model may correspond to either an increased demand of heat, or an increase of electricity specific demand, in the energy system model. The same logic applies to increased use of electricity in the top-down model. This lack of direct correspondence is a general challenge when we want to link top-down and bottom-up models. For simplicity, we assume that the combined use of gas and electricity in the top-down model gives rise to the same relative increase for heat and electricity specific demand in the bottom-up model.

Furthermore, the top-down parameter $io_{gas,ele}$ (gas input share of the electricity product) is estimated from the bottom-up model:

$$io_{gas,ele} = \frac{x^{act}_{2026,gaspower}}{x^{act}_{2026,electricitydemand}} \tag{17}$$

The gas input share in the top-down model is approximated by the gaspower share of electricity production in the bottom-up model. This relation needs to be calibrated from the problem case that is investigated.

With these equations connecting the models, the parameter input is updated after each model solve, and hard-linked iterations are run until convergence is reached. Convergence is assumed when the relative change from one iteration to the next in 1) total energy system cost, 2) gas input share to electricity sector and 3) projected future demand is below a small tolerance (10^{-6}).

2.4. Reformulation from linear program to mixed complementarity problem

Complementarity problems generalize linear programs (LP), quadratic programs (QP), and convex nonlinear programs (NLPs) [48]. A linear or nonlinear program can be posed as a complementarity problem based on Karush-Kuhn-Tucker (KKT) optimality conditions, by forming the Lagrangian and differentiating. Thus, the bottom-up linear program can be reformulated and expressed as an MCP. The bottom-up linear program expressed as an MCP is presented below.

Dual variables $u^{capact}_{t,p}$, $u^{combal}_{t,c}$, $u^{capup}_{t,p}$ and $v^{comprd}_{t,c}$ are defined for the corresponding bottom-up model constraints. The dual constraints related to variables $i^{cap}_{t,p}$, $x^{act}_{t,p}$ and $x^{prd}_{t,c}$from the energy system model are provided below. The full bottom-up KKT system is reported in the first seven complementarity conditions of appendix 8.1, listed in equations (A.1) to (A.8).
KKT condition perpendicular to variable $i^{cap}_{t,p}$:

$$(1 - salvage_{t,p}) C^{cap}_{t,p} + \sum_{t'=t}^{\min(2026, t+L_p-1)} C^{fom}_{t',p} - \sum_{t'=t}^{\min(2026, t+L_p-1)} A^f_p \cdot \alpha^{capact}_p \cdot u^{capact}_{t',p} + u^{capup}_{t,p} \geq 0, \quad \forall\ t \in [2015, 2026],\ p \in P_{prod} \tag{18}$$

KKT condition perpendicular to variable $x^{act}_{t,p}$:

$$C^{act}_{t,p} + u^{capact}_{t,p} + \left(\sum_{c \in C_p} -1 + \sum_{c' \in C'_p} \frac{1}{\phi_{p,c,c'}} \right) \cdot u^{combal}_{t,c} + \sum_{c \in C_p} v^{comprd}_{t,c} \geq 0, \quad \forall t \in [2015, 2026], p \in P_{prod} \tag{19}$$

KKT condition perpendicular to variable $x^{prd}_{t,c}$:

$$C^{prd}_{t,c} - v^{comprd}_{t,c} \geq 0 \quad , \forall t \in [2015, 2026], c \in C_{prod} \tag{20}$$

This MCP reformulation of the bottom-up model may be used for hard-linking the models, in the same way as the LP formulation.

2.5. Integrated mixed complementarity problem formulation

Instead of solving hard-linked models by exchanging model results, all variables and constraints, as well as the linking expressions, may be collected into one integrated model.

Since the CGE model is formulated as an MCP, the bottom-up reformulation gives us the opportunity to collect all variables, equations and complementarity conditions into one integrated MCP formulation. The linking parameters $D_{t,c}$ and $io_{gas,ele}$ are expressed endogenously in this integrated model, instead of being exchanged iteratively between the hard-linked models.

The MCP formulations reflect the reaction curve for each player, and are developed from the KKT conditions. A solution from the integrated MCP model constitutes a Nash equilibrium, where no player may gain from a unilateral change of strategy if the strategies of the others remain unchanged. Each player is assumed to take his decision simultaneously, and each player is assumed to know the equilibrium strategies of the other players.

The integrated MCP-model is provided in appendix 8.1.

2.6. Integrated nonlinear program formulation

The CGE model may also be posed as an NLP problem. By assuming strictly positive prices for all goods and factors, and that all four firms are producing in the equilibrium solution, we can define all equations as equalities and solve the CGE model as an NLP. This assumption is not unreasonable as long as the CGE model is rather aggregated, with few sectors. The NLP formulation of the CGE model may be used for hard-linking the separate models, in the same way as the MCP model.

The CGE model does not have any objective function (the model just solves a system of nonlinear equations in order to find an equilibrium solution.). We may therefore extend the NLP CGE model with the bottom-up variables, equations *and objective function*, and include the affected linking parameters $D_{t,c}$ and $io_{gas,ele}$ using the endogenous mathematical expressions defined in 2.3.

When the NLP CGE model and the bottom-up LP model is fully integrated rather than hard-linked, the resulting model is equivalent to a multi-follower bi-level optimization problem, with the energy system at the upper level and the firms and household at the lower level. The solution from this model will constitute a Stackelberg equilibrium.

The integrated LP-NLP hybrid model is reported in appendix 8.2.

3. Analysis and results

In this section the four hard-linked and the two integrated model setups are introduced, and an instructive test problem is described in detail. The hard-linking convergence is described. All model variants are run over a problem grid defining 2501 problem instances. Equilibrium solutions are compared and convergence results are described.

3.1. Model setups

We implement four variants of hard-linking (alternatives A-D), see Table 2. The bottom-up model is either expressed as a linear programming problem (being solved by the CPLEX solver from IBM), or as a mixed complementarity problem (being solved by the PATH solver from University of Wisconsin - Madison). The top-down model is either expressed as a mixed complementarity problem (being solved by the PATH solver), or as a nonlinear programming problem (being solved by the CONOPT solver from ARKI Consulting and Development).

As explained in the previous section, we have two integrated model setups, see Table 3. The bottom-up and top-down models are run together, by collecting all variables and constraints into an integrated hybrid model. The integrated models are solved by expressing them either as one mixed complementarity problem (being solved by the PATH solver), or as one nonlinear programming problem (being solved by the CONOPT solver).

The six different setups are shown in Fig. 5. All our hybrid models are implemented in GAMS.[5]

In order to demonstrate the dynamic behavior of the models, we run an instructive test problem where we assume that available labor in the CGE model increases by 10% compared with the base year. We also assume that the energy system has unused potential for hydropower electricity production. Thus, the bottom up model invests in hydropower production facilities, and the share of gaspower in the electricity mix decreases (see Fig. 6 in the next section). The bottom-up model is dynamic and solves for each year, while the static CGE model only solves for the future equilibrium in 2026 (see time dimension depicted in Fig. 4). For simplicity we assume that demand for energy services in the bottom-up model grows linearly from the base year to the future demand derived from the CGE model. A dynamic CGE model would provide demand also in intermediate years.

Table 2
Hard-linked model setups.

Bottom-up\Top-down	MCP	NLP
LP	A	C
MCP	B	D

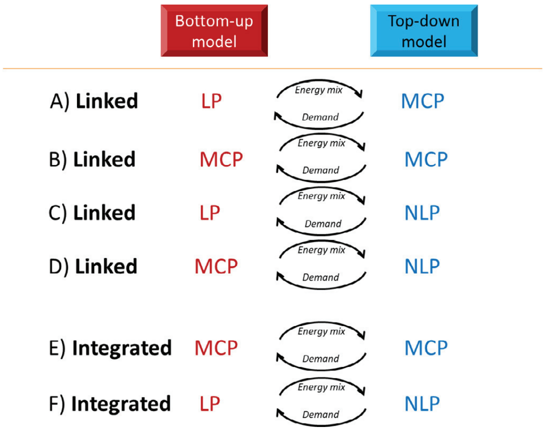

Fig. 5. Hybrid model setups.

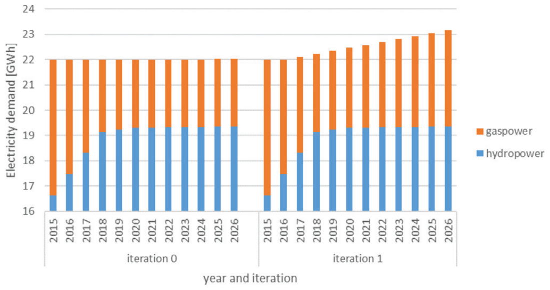

Fig. 6. Bottom-up model response from demand increase in iteration 1. Iteration 0 is initial bottom-up solution.

Table 3
Integrated model setups.

Bottom-up\Top-down	MCP	NLP
LP		F
MCP	E	

All input parameters are provided in appendix 8.3.

Results from the test problem are shown in the next section,

---

[5] General Algebraic Modeling System, see www.gams.com.

Table 4
Relative changes in Social Accounting Matrix from increasing labor supply by 10% [all values in per cent] for iteration 1.

	gas	ele	man	non	L	K	hou	Tot	Price increase	Volume increase
gas		10.1%	10.6%	10.8%			7.7%	10.1%	4.5%	**5.4%**
ele	10.2%	10.1%	10.6%	10.8%			8.2%	10.1%	4.6%	**5.3%**
man	10.3%	10.2%	10.7%	10.9%			8.7%	10.7%	4.7%	5.7%
non	9.1%	9.0%	9.5%	9.7%			9.9%	9.7%	3.6%	6.0%
L	11.2%	11.1%	11.1%	9.9%				*10.0%*	*0%*	*10.0%*
K	12.2%	13.1%	12.2%	7.9%				9.4%	9.4%	*0%*
hou					*10.0%*	9.4%		9.7%		
Tot	10.1%	10.1%	10.7%	9.7%	*10.0%*	9.4%	9.7%		4.7%	5.7%

demonstrating the dynamic interplay between the models. Results from 4 hard-linked hybrid models and 2 integrated hybrid models are compared. Then all 6 hybrid model setups are run over a problem grid where *both* the growth of capital and labor are adjusted in the top-down model. Again, results from our 4 hard-linked and 2 integrated models are compared.

3.2. Hybrid model interplay

Let us demonstrate the interplay between the models, by showing in detail what happens in the first iteration of linking the top-down and bottom-up model. The linking dynamics is driven by a labor increase of 10% in the CGE model. The CGE model utilizes the increased labor supply and finds a new equilibrium. Table 4 shows relative changes in iteration 1. Note that the price of labor is defined as numeraire.

The combined volume demand increase for energy (consisting of gas and electricity, shown in bold in Table 4) of 5.3% is transferred to the bottom-up model. The bottom-up response in terms of electricity production is shown in Fig. 6.

The bottom-up model invests in available capacity of hydropower after 2015, but the demand increase from iteration 0 to iteration 1 is supplied from gas power. The 2026 share of gaspower in iteration 1 still decreases compared with the 2015 share in iteration 0. The top-down model needs less gas to produce the same amount of electricity as before. This change triggers a new adjustment of the equilibrium in the top-down model.

When it comes to the final convergence of the linking, Fig. 7 shows the relative increase in household utility by iteration. The initial increase of labor supply results in a relative increase in household utility of 7.1% in 2026 compared with 2015. The subsequent reduction of gas in the future electricity production raises household utility further to an increase of 8.0% compared with 2015.

Since energy production becomes cheaper, the top-down model reallocates resources, and the perhaps surprising effect is that energy demand decreases after the initial increase (see Fig. 8).[6]

Fig. 9 shows the relative prices in 2026 by iteration, having the price of labor as numeraire. All prices are assumed to be equal to unity in the base year. The labor supply increases, so all other prices increase initially. Electricity production becomes cheaper in the bottom-up model, and the gas input in the top-down model decrease during iterations. The relative price of electricity decreases compared to the labor price. Capital becomes the scarce

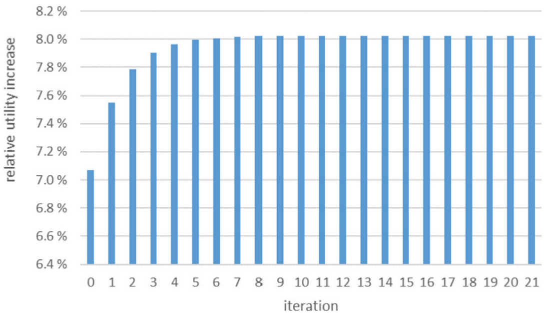

Fig. 7. Relative increase in household utility in 2026 compared with 2015, by iteration.

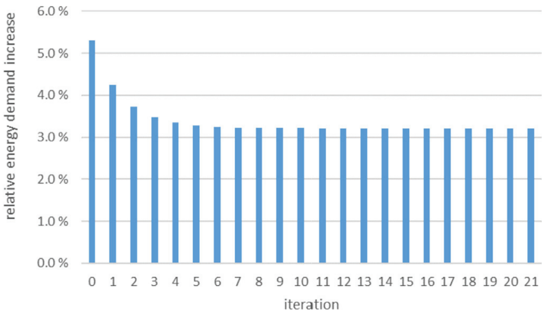

Fig. 8. Relative energy demand increase by iteration.

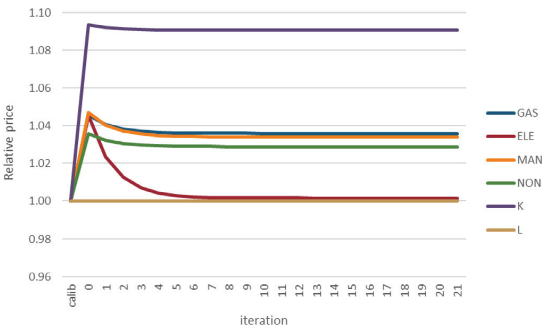

Fig. 9. Relative prices by iteration.

---

[6] This effect depends on the volume of hydropower potential compared to the growth of the economy. A higher labor (or capital) growth would increase the energy demand further, and exhaust the relative hydropower benefits. Increased use of gas will be required for electricity production, and $io_{gas,ele}$ adjustments will make electricity more expensive (instead of cheaper as seen in Fig. 9). The top-down model will have to reallocate more resources to energy production. The development will be reversed, resulting in decreasing utility and increasing energy demand during iterations following the initial one.

factor with the highest price, while prices of gas, manufacturing and non-manufacturing are grouped in the middle.

An integrated model setup does not produce intermediate solutions from iterations towards a converged solution. Instead the solver knows the whole integrated model, and finds the solution directly. Fig. 10 shows total energy system costs from the linked model setup by iteration, compared with solutions from our two integrated model setups shown as horisontal lines.

The linked energy system costs follow the same pattern as the energy demand shown in Fig. 8. The integrated models directly find solutions with the same level of energy system costs as the linked models. Since the solver can aim for the integrated solution directly instead of solving many intermediate problems, the solution process of the integrated models is much faster than the linked models. (Comparisons of elapsed time for the different models are provided in Table 5.)

Fig. 10 shows that all the models end up with similar energy system costs. A closer inspection of the solutions shows that the integrated LP-NLP model finds a solution with slightly lower costs than the other models (see Fig. 11), but still with increased household utility. This solution pareto-dominates the solution from the linked models. The integrated MCP model finds the same solution as the linked models. The differences between the solutions are small in our test problem, energy system cost decreases by 0.04%, while household utility increases by 0.01%. This may seem surprising, but it is important to realize that the integrated MCP and integrated LP-NLP are not identical models. Our integrated MCP model includes the reaction functions of the different players, but the assumption is that their decisions are made simultaneously and there is no first mover advantage. In the integrated LP-NLP model the energy system employs a first mover advantage, and makes its decision before the players in the top-down model, resembling a multi-follower Stackelberg decision process. In our problem, the household follower (in the CGE model) also benefits from lower energy system costs. Thus, the integrated LP-NLP solution pareto-dominates the integrated MCP solution.

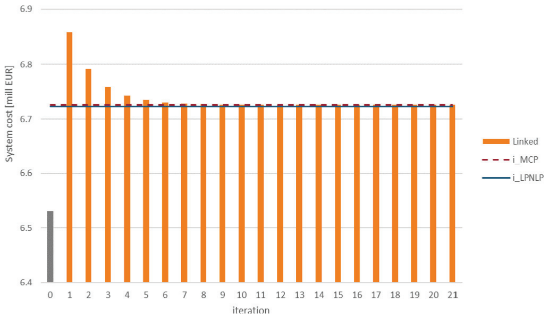

Fig. 10. Energy system costs by iteration, compared with solutions from integrated models.

Table 5
Elapsed time for model variants, solving 2501 problem instances.

Hybrid setup	Model variant	Elapsed (h:m:s)	Solver versions
Hard-linked	LP-NLP	6:41:42	BU: Cplex 12.7.0.0 TD: Conopt 3.17C
Hard-linked	LP-MCP	8:30:23	BU: Cplex 12.7.0.0 TD: Path 4.7.04
Hard-linked	MCP-NLP	8:04:48	BU: Path 4.7.04 TD: Conopt 3.17C
Hard-linked	MCP-MCP	9:46:35	Path 4.7.04
Integrated	NLP	**0:07:15**	Conopt 3.17C
Integrated	MCP	**0:10:31**	Path 4.7.04

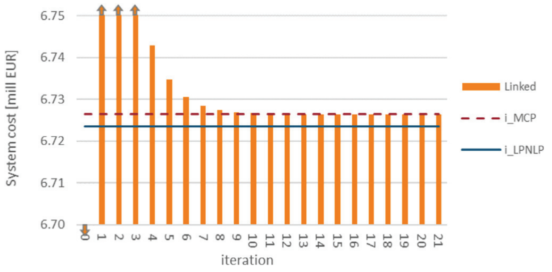

Fig. 11. Energy system costs, showing difference between solutions.

The reason for the improvement is increased hydropower investment in the integrated LP-NLP model. Our problem allows considerable investments in new hydropower production from 2016, but available natural resources get exhausted, and after 2020 only small investments are possible. Hydropower investments are decided in the bottom-up model, and have the side effect of affecting the Leontief production function of electricity production in the top-down model. The top-down model observes less use of natural gas in the bottom-up electricity production, which reduces the cost of electricity and consequently demand increases. This demand increase makes the hydropower investment profitable in the bottom-up model.

The linked models and the integrated MCP model do not make the hydropower investment in 2026, because the energy demand in the bottom-up model is too low to make it profitable. In the integrated LP-NLP version, the solver sees the indirect relationships and invests in additional hydropower in 2026. The result is both lower energy system costs and increased household utility.

The hard-linked models are solved separately, and iterates towards an equilibrium. In our test problem, the four hard-linked setups reach the same equilibrium as the integrated MCP.

3.3. *Multiple problem instances*

A grid of problem instances is defined, where available labor and capital in the CGE model are gradually adjusted. All six model configurations are given the same set of problem instances. Capital is increased by a factor running from 1 to 1.3 (30% increase) in steps of 0.005, while labor is increased by a factor running from 1 to 1.2 (20% increase) in steps of 0.005. This produces $61*41 = 2501$ problem instances for our six model setups.

All the hard-linked model configurations find the same solution in every problem instance. They typically also follow the same iteration path – except in 34 out of 2501 problem instances where numerical differences (below the solver tolerance) create an additional iteration.[7] The integrated MCP model finds the same solution as the hard-linked models in every problem instance. As noticed in the previous section, the integrated LP-NLP model finds a different (and improved in terms of lower energy system costs) equilibrium in some problem instances. This is depicted in Fig. 12.

Fig. 13 shows the set of problem instances. Instances where the integrated LP-NLP finds an improved energy system cost solution are colored. This happens in 1067 out of 2501 instances (43%).

The problem instances were solved on a Dell Precision T7600 with two Intel Xeon CPU E5-2650 2 GHz processors using GAMS

---

[7] Solving the CGE as an MCP problem using the PATH solver compared to solving the CGE as an NLP problem using the CONOPT solver produces one extra iteration in 34 out of 2501 problem instances.

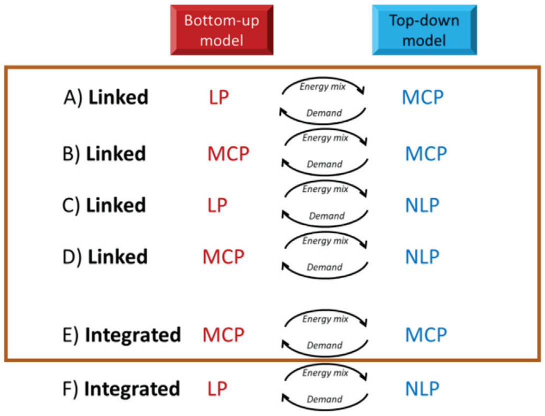

Fig. 12. Model configurations finding the same solutions.

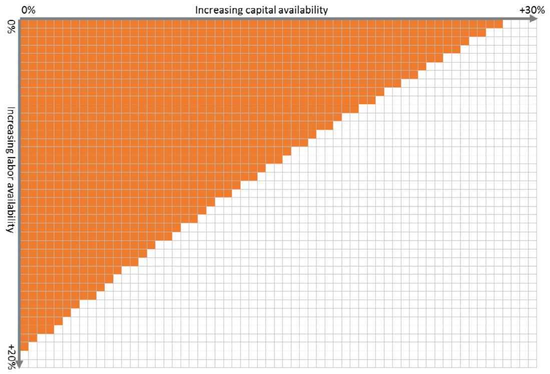

Fig. 13. Problem instances where the integrated LP-NLP model finds improved solution.

version 24.8.3 under Windows 7 SP1 version 6.1.7601 with 32 GB RAM. Computer elapsed time for solving 2501 problem instances are shown in Table 5.

4. Discussion

In this section results are discussed, providing a basis for answering the research questions.

4.1. Equilibria using hard-linking and integration

Four hard-linked and two integrated versions of hybrid modeling have been compared. Our hard-linking method of exchanging primal variable values represents a decomposition of the situation where each player makes his decision simultaneously. The strategies of the other players are signaled through the iterations between the models. All four hard-linked model configurations find the same converged solution in every problem instance. This indicates that the different model formulations are equivalent.

Our integrated MCP version is constructed by extending the CGE model with the KKT conditions from the bottom-up model (represented in the bottom-up MCP reformulation). Thus, an equilibrium problem consisting of each player's KKT conditions together with market clearing conditions is solved, obtaining a generalized Nash equilibrium. In this model each player knows the equilibrium strategies of the other players, and each player makes his decision simultaneously. The integrated MCP finds the same solution as the hard-linked models in all problem instances. This indicates that iterating between linked bottom-up and top-down models will usually produce the same equilibrium solution as the integrated model. This is comforting, since many hybrid approaches consist of soft-linking top-down and bottom-up models. Hard-linking the two models may be seen as a decomposition of the underlying integrated model.

The integrated LP-NLP, on the other hand, finds different solutions. As our results indicate, the integrated LP-NLP and the integrated MCP do not represent the same underlying problem. The integrated LP-NLP formulation corresponds to a multi-follower bilevel problem, with the energy system model as the leader and the CGE players (firms and household) as followers. The leader and the followers play a Stackelberg game, and in some problem instances a Stackelberg equilibrium which differs from the hard-linked and integrated MCP Nash equilibrium is found. Here, the energy system is endowed with a first mover advantage, and the Stackelberg equilibrium represents an improved solution for the energy system (lower system costs). The energy system foresees how the household and firms will react, and is able to decrease the overall energy system cost by making a strategic investment. Interestingly, the CGE household (follower) also profits in the Stackelberg equilibrium, being able to increase its utility. This is due to improved resource utilization enabled by the cost reduction in the energy system. The CGE firms (followers) reach the same zero profit as before, being indifferent between the solutions. Thus, the Stackelberg equilibrium pareto-dominates the generalized Nash equilibrium from the integrated MCP model and the hard-linked models.

The integrated MCP model and the integrated LP-NLP version represent two different situations, the first approach assuming simultaneous decisions and the second a leader-follower formulation. It is interesting that the LP-NLP provides a computationally tractable formulation for a Stackelberg model. In this reformulation, as the energy system can be optimized under the first mover advantage, it manages to reduce the energy system costs by a larger extent than the other setups. In turn, this allows to endow the economy with cheaper energy sources, leading to a general resource efficiency improvement in the whole economic system. The competitive economic setup implies that the benefit of this efficiency improvement is collected by the household. Thus, a lower energy system cost induces a higher household utility level in the integrated LP-NLP model.

Which model that would be preferred, depends on the decision and information structure of the underlying situation. It may be an unrealistic representation to model the energy system as a leader and CGE players as followers. Nevertheless, it is interesting that this produce a pareto-dominant equilibrium with higher value for society. It is an interesting question from a society perspective whether policy measures could be shaped to achieve that equilibrium.

4.2. Hard-linking versus integration: is there a correct choice?

One advantage of linking models, is that the models can be kept separated and intact. The models rely on data collected from different data sources, and often with different product granulation and time resolutions. Bottom-up models focus on quantities and build on national energy balances, while top-down models deal with economic values and build on national accounts. An engineer or an economist starting to work with one of these modeling types has to learn a lot of details in order to run useful analyses. Integrating such models demands combined knowledge and modeling skills from both areas, while linking allows us to retain both models separate and also retain the consistency of each database. This makes linking a natural first step to combine the different areas of expertise.

The integrated approach that has been presented maintains this advantage by merging the formulations of the two problem classes using representations of the linking constraints. The demonstrated approach improves current linking practices, without building new models. The demonstrated integration between the energy system and the whole economy can be implemented across all sectors (full-link). Thus, bottom-up data and expertise could be utilized efficiently. Earlier integrated models, like Böhringer and Rutherford [18] took a different approach, by providing a formulation with a detailed integration of bottom-up technologies in a CGE model, but only for a limited number of sectors and hence not giving a full-link formulation. One of our main contributions is to bring the advantages mentioned above into full-link integrated models.

Hard-linking the models also leads to other challenges. Convergence criteria must be defined and implemented. Programming code enabling linking, control of code execution, logging and error detection needs to be implemented. Cycling may occur during iterations. An integrated hybrid model will allow the solver to handle these kinds of problems, which is a great advantage. A disadvantage is that one integrated model becomes much bigger than the separate models, and thus is harder to solve than solving each model separately.

From the perspective of solution times, integrated models seem at first glimpse better than linked models. This is also confirmed by Böhringer and Rutherford [18] who implemented an efficient decomposition method for their integrated model. Computational time spent by the solver may in theory be either higher or lower with an integrated model compared to a hard-linked model. If both the bottom-up and top-down models are demanding to solve on their own, then linking may be the only feasible way to move forward.

5. Conclusions

We have implemented both hard-linking and integration between a top-down computable general equilibrium model and a bottom-up energy system model. Our main contribution is the development of a full-link integrated model. Our approach is generic, and investigates the possibility to integrate instead of hard-linking hybrid models. Four implementations of hard-linked models and one equivalent integrated full-link MCP hybrid model produced the same solutions in all 2501 problem instances. The integration between the energy system and the whole economy that we demonstrate, can be implemented across all sectors (full-link). Our experiments show that when the solver has knowledge of the full integrated model, time-consuming linking iterations between large-scale models may be avoided as well as avoiding a lot of programming code that otherwise must be customized for model linking. The integrated model maintains the advantages of the linked approach by keeping the CGE and bottom-up formulations and their respective data sets intact, and avoids its computational problems by solving the full model directly.

The work also shows that two closely related implementations of integrated models may find different solutions on the same problem instances. A reformulation into an integrated optimization NLP instead of an MCP, represents a Stackelberg formulation where the energy system has a first mover advantage and the firms and household act as followers. In many cases this integrated LP-NLP model finds a Stackelberg equilibrium that differ from the generalized Nash equilibrium found by the integrated MCP and the hard-linked models. Interestingly the Stackelberg equilibrium pareto-dominates the generalized Nash equilibrium in our test cases.

Further research could provide improved methods to update the production functions based on the bottom-up model. CES functions tend toward factor share preservation, so an alternative might be to update CES factor shares instead of Leontief coefficients. Furthermore, a recursive dynamic CGE model would provide opportunities for information exchange in intermediate years, providing improved coupling along the time dimension.

Acknowledgements

This work was made possible by the financial support of the Norwegian Research Council through the funding of the project Regional effects of energy policy (216513), and by the financial support from Enova SF for the doctoral work of Per Ivar Helgesen.

The authors would like to thank Paolo Pisciella, Ruud Egging and Arne Lind for their valuable comments and suggestions.

8. Appendix

The complete integrated models and input parameters are listed in the appendix.

8.1. Integrated mixed complementarity problem − mathematical formulation

KKT_CAP_INVEST ($\perp i_{t,p}^{cap}$):

$$(1 - salvage_{t,p})C_{t,p}^{cap} + \sum_{t'=t}^{\min(2026,t+L_p-1)} C_{t',p}^{fom} - \sum_{t'=t}^{\min(2026,t+L_p-1)} A_p^f \cdot \alpha_p^{capact} \cdot u_{t',p}^{capact} + u_{t,p}^{capup} \geq 0, \quad \forall\ t \in [2015, 2026],\ \ p \in P_{prod} \tag{A.1}$$

KKT_VAR_ACT ($\perp x_{t,p}^{act}$):

$$C_{t,p}^{act} + u_{t,p}^{capact} + \left(\sum_{c \in C_p} -1 + \sum_{c' \in C_p'} \frac{1}{\phi_{p,c,c'}} \right) \cdot u_{t,c}^{combal} + \sum_{c \in C_p} v_{t,c}^{comprd} \geq 0, \quad \forall t \in [2015,2026], p \in P_{prod} \tag{A.2}$$

KKT_COM_PRD ($\perp x_{t,c}^{prd}$):

$$C_{t,c}^{prd} - v_{t,c}^{comprd} \geq 0 \quad , \forall t \in [2015, 2026], \quad c \in C_{prod} \tag{A.3}$$

CAPACT: Process activity $\leq$ capacity ($\perp u_{t,p}^{capact}$):

$$x_{t,p}^{act} \leq \sum_{v=\max(2015,t-L_p+1)}^{t} A_p^f \cdot \alpha_p^{capact} \cdot i_{v,p}^{cap} + A_p^f \cdot \alpha_p^{capact} \cdot \rho_{t,p} \cdot I_{2015,p}^{cap}, \quad \forall t \in [2015,2026], p \in P_{prod} \tag{A.4}$$

COMBAL: Use of commodity $\leq$ commodity supply ($\perp u_{t,c}^{combal}$):

$$D_{t,c} + \sum_{p \in P_c^{in}, c' \varepsilon C} \frac{x_{t,p}^{act}}{\phi_{p,c,c'}} \le \sum_{p \in P_c^{out}} x_{t,p}^{act}, \ \forall \ t \in [2015, 2016], \ c \in C \backslash C_{supply} \tag{A.5}$$

$$\begin{aligned} & D_{2016,c} + D_{2016,c} \cdot \frac{x_{gas} + x_{ele} - x_{gas}^0 - x_{ele}^0}{x_{gas}^0 + x_{ele}^0} \cdot \frac{(t-2016)}{(2026-2016)} \\ & + \sum_{p \in P_c^{in}, c' \varepsilon C} \frac{x_{t,p}^{act}}{\phi_{p,c,c'}} \\ & \le \sum_{p \in P_c^{out}} x_{t,p}^{act}, \forall t \in [2017, 2026], c \in C \backslash C_{supply} \end{aligned} \tag{A.6}$$

COMPRD: Commodity production must equal corresponding process activity $(\perp v_{t,c}^{comprd})$:

$$x_{t,c}^{prd} = \sum_{p \in P_c^{out}} x_{t,p}^{act}, \forall t \in [2015, 2026], c \in C_{prod} \tag{A.7}$$

CAPUP: Capacity upper bounds $(\perp u_{t,p}^{capup})$:

$$i_{t,p}^{cap} \le U_{t,p}^{cap} \forall t \in [2015, 2026], p \in P_{prod} \tag{A.8}$$

Zero profit conditions $(\perp x_i)$:

$$p_i \cdot x_i = p_l \cdot L_i + p_k \cdot K_i + \sum_{j \in I} io_{j,i} \cdot p_j \cdot x_i, \ \forall i \in I \backslash \{ELE\} \tag{A.9}$$

$$\begin{aligned} p_i \cdot x_i = p_l \cdot L_i + p_k \cdot K_i + \sum_{j \in I \backslash \{gas\}} io_{j,i} \cdot p_j \cdot x_i + \frac{x_{2026,gaspower}^{act}}{x_{2026,electricitydemand}^{act}} \cdot p_{GAS} \\ \cdot x_i, i \in \{ELE\} \end{aligned} \tag{A.10}$$

Market clearing conditions for goods $(\perp p_i)$:

$$c_i + \sum_{j \in I} io_{i,j} \cdot x_j = \ x_i, \ \forall i \in I \backslash \{GAS\} \tag{A.11}$$

$$c_i + \sum_{j \in I \backslash \{ELE\}} io_{i,j} \cdot x_j + \frac{x_{2026,gaspower}^{act}}{x_{2026,electricitydemand}^{act}} \cdot x_{ELE} = x_i, i \in \{GAS\} \tag{A.12}$$

Market clearing conditions for production factor labor $(\perp p_l)$:

$$\sum_{i \in I} L_i = LS \tag{A.13}$$

Market clearing conditions for production factor capital $(\perp p_k)$:

$$\sum_{i \in I} K_i = KS \tag{A.14}$$

Income balance $(\perp h)$:

$$h = p_k \cdot KS + p_l \cdot LS \tag{A.15}$$

Household consumption $(\perp c_i)$:

$$p_i \cdot c_i = p_i \cdot \mu_i^h + \alpha_i^h \cdot \left(h - \sum_{j \in I} p_j \cdot \mu_j^h \right), \forall i \in I \tag{A.16}$$

Definition, firm's use of labor $(\perp L_i)$:

$$L_i = \frac{x_i}{a_i^F} \cdot \left(\frac{1 - \gamma_i^F}{p_l} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k^{\left(1-\sigma_i^F\right)} + \left(1 - \gamma_i^F\right)^{\sigma_i^F} \cdot p_l \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)}, \forall i \in I \tag{A.17}$$

Definition, firm's use of capital $(\perp K_i)$:

$$K_i = \frac{x_i}{a_i^F} \cdot \left(\frac{\gamma_i^F}{p_k} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k + \left(1 - \gamma_i^F\right)^{\sigma_i^F} \cdot p_l \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)}, \forall i \in I \tag{A.18}$$

8.2. Integrated nonlinear program – mathematical formulation

Minimize system costs:

$$\min_{i_{t,p}^{cap}, x_{t,p}^{act}, x_{t,c}^{prd}} \left(\begin{aligned} & \sum_{t=2015}^{2026} \sum_{p \in P} (1 - salvage_{t,p}) \left(C_{t,p}^{cap} \bullet i_{t,p}^{cap} \right) \\ & + \sum_{v=2015}^{2026} \sum_{p \in P} \sum_{t=v}^{\min(2026, v+L_p-1)} C_{t,p}^{fom} \bullet i_{v,p}^{cap} + \sum_{t=2015}^{2026} \sum_{p \in P} C_{t,p}^{act} \bullet x_{t,p}^{act} + \\ & \sum_{t=2015}^{2026} \sum_{c \in C} C_{t,c}^{prd} \bullet x_{t,c}^{prd} \end{aligned} \right) \tag{A.19}$$

subject to
CAPACT: Process activity<Roman> = </Roman>capacity

$$\begin{aligned} x_{t,p}^{act} \le & \sum_{v=\max(2015, t-L_p+1)}^{t} A_p^f \cdot \alpha_p^{capact} \cdot i_{v,p}^{cap} \\ & + A_p^f \cdot \alpha_p^{capact} \cdot \rho_{t,p} \cdot I_{2015,p}^{cap}, \forall t \in [2015, 2026], p \in P_{prod} \end{aligned} \tag{A.20}$$

COMBAL: Use of commodity<Roman> = </Roman>Commodity supply

$$D_{t,c} + \sum_{p \in P_c^{in}, c' \varepsilon C} \frac{x_{t,p}^{act}}{\phi_{p,c,c'}} \le \sum_{p \in P_c^{out}} x_{t,p}^{act}, \forall t \in [2015, 2016], c \in C \backslash C_{supply} \tag{A.21}$$

$$\begin{aligned} & D_{2016,c} + D_{2016,c} \cdot \frac{x_{gas} + x_{ele} - x_{gas}^0 - x_{ele}^0}{x_{gas}^0 + x_{ele}^0} \cdot \frac{(t-2016)}{(2026-2016)} \\ & + \sum_{p \in P_c^{in}, c' \varepsilon C} \frac{x_{t,p}^{act}}{\phi_{p,c,c'}} \\ & \le \sum_{p \in P_c^{out}} x_{t,p}^{act}, \forall t \in [2017, 2026], c \in C \backslash C_{supply} \end{aligned} \tag{A.22}$$

COMPRD: Commodity production must equal corresponding process activity

$$x_{t,c}^{prd} = \sum_{p \in P_c^{out}} x_{t,p}^{act}, \forall t \in [2015, 2026], c \in C_{prod} \tag{A.23}$$

CAPUP: Capacity upper bounds

$$i_{t,p}^{cap} \le U_{t,p}^{cap} \forall t \in [2015, 2026], p \in P_{prod} \tag{A.24}$$

Zero profit conditions:

$$p_i \cdot x_i = p_l \cdot L_i + p_k \cdot K_i + \sum \sum_{j \in I} io_{j,i} \cdot p_j \cdot x_i, \forall i \in I \backslash \{ELE\} \tag{A.25}$$

$$\begin{aligned} p_i \cdot x_i = {} & p_l \cdot L_i + p_k \cdot K_i + \sum_{j \in I\{gas\}} io_{j,i} \cdot p_j \cdot x_i \\ & + \frac{x_{2026,gaspower}^{act}}{x_{2026,electricitydemand}^{act}} \cdot p_{GAS} \cdot x_i, i \in \{ELE\} \end{aligned} \tag{A.26}$$

Market clearing conditions for goods:

$$c_i + \sum_{j \in I} io_{i,j} \cdot x_j = x_i, \forall i \in I \backslash \{GAS\} \tag{A.27}$$

$$c_i + \sum_{j \in I\{ELE\}} io_{i,j} \cdot x_j + \frac{x_{2026,gaspower}^{act}}{x_{2026,electricitydemand}^{act}} \cdot x_{ELE} = x_i, i \in \{GAS\} \tag{A.28}$$

Market clearing condition for production factor labor:

$$\sum_{i \in I} L_i = LS \tag{A.29}$$

Market clearing condition for production factor capital:

$$\sum_{i \in I} K_i = KS \tag{A.30}$$

Income balance:

$$h = p_k \cdot KS + p_l \cdot LS \tag{A.31}$$

Household consumption:

$$p_i \cdot c_i = p_i \cdot \mu_i^h + \alpha_i^h \cdot \left(h - \sum_{j \in I} p_j \cdot \mu_j^h \right), \forall i \in I \tag{A.32}$$

Definition, firm's use of labor:

$$L_i = \frac{x_i}{a_i^F} \cdot \left(\frac{1-\gamma_i^F}{p_l} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k^{\left(1-\sigma_i^F\right)} + \left(1-\gamma_i^F\right)^{\sigma_i^F} \cdot p_l^{\left(1-\sigma_i^F\right)} \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)}, \\ \forall i \in I \tag{A.33}$$

Definition, firm's use of capital:

$$K_i = \frac{x_i}{a_i^F} \cdot \left(\frac{\gamma_i^F}{p_k} \right)^{\sigma_i^F} \left(\gamma_i^{F\sigma_i^F} \cdot p_k^{\left(1-\sigma_i^F\right)} + \left(1-\gamma_i^F\right)^{\sigma_i^F} \cdot p_l^{\left(1-\sigma_i^F\right)} \right)^{\left(\frac{\sigma_i^F}{\left(1-\sigma_i^F\right)} \right)}, \\ \forall i \in I \tag{A.34}$$

8.3. *Input data*

Table 6
Energy system parameters with time dimension

Parameter	Unit	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Investment cost $C_{t,p}^{cap}$													
Hydropower (50 years lifetime)	kNOK/MW	12200	12200	12200	12200	12200	12200	12200	22200	22200	22200	22200	22200
Gaspower (25 years lifetime)	kNOK/MW	3200	3200	3200	3200	3200	3200	3200	3200	3200	3200	3200	3200
Gasburner (25 years lifetime)	kNOK/GWh/a	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3
Electric heating (25 years lifetime)	kNOK/GWh/a	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100
Fixed operating and maintenance cost $C_{t,p}^{fom}$													
Hydropower	kNOK/MW	205.23	205.23	205.23	205.23	205.23	205.23	205.23	205.23	205.23	205.23	205.23	2300
Gaspower	kNOK/MW	96	96	96	96	96	96	96	96	96	96	96	96
Gasburner	kNOK/GWh/a	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Electric heating	kNOK/GWh/a	2	2	2	2	2	2	2	2	2	2	2	2
Variable cost $C_{t,p}^{act}$													
Hydropower	kNOK/GWh	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37
Production cost $C_{t,c}^{prd}$													
Natural gas	kNOK/GWh	130	153	130	130	130	130	130	130	130	130	130	130
Salvage value share in 2026 by investment year													
Hydropower (50 years)	(unitless)	0.76	0.78	0.80	0.82	0.84	0.86	0.88	0.90	0.92	0.94	0.96	0.98
Gaspower (25 years)	(unitless)	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96
Gasburner (25 years)	(unitless)	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96
Electric heating (25years)	(unitless)	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96
Bound on capacity investment $U_{t,p}^{cap}$													
Hydropower	MW	2	0.1	0.1	0.1	0.01	0.01	0.001	0.001	0.001	0.001	0.001	0.001
Demand $D_{t,c}$													
Heat demand	GWh	14.2843	14.2857	(demand in 2026 defined from top-down model, linearly interpolated to 2016)									
Electricity demand	GWh	21.9978	22	(demand in 2026 defined from top-down model, linearly interpolated to 2016)									

Table 7
Energy system parameters by process

Technology	Availability of capacity A_p^f	Capacity to activity conversion factor α_p^{capact}	Technical lifetime L_p (years)
Hydropower	0.95	8.76	50
Gaspower	1	8.76	25
Gasburner	1	1	25
Electric heating	1	1	25

Table 8
Energy system parameters for commodity conversion processes

Technology	Input commodity	Output commodity	Flow conversion factor $\phi_{p,c,c'}$
Gaspower	Natural gas	Electricity	0.4
Gasburner	Natural gas	Heat	0.95
Elheater	Electricity	Heat	1.0
Hydropower	Hydro	Electricity	1.0

Table 9
Input parameters to top-down CGE model.

	gas	ele	man	Non
Capital-Labor substitution elasticity σ_i^F	0.9	0.8	0.9	1.2
Income elasticity of demand σ_i^h	0.7	0.8	0.9	1.2

Remaining parameters for the top-down CGE model

To calculate remaining model parameters, we define all relative prices to be equal to one in the base year, and we define the following intermediate parameters:

K_i^{base} is capital use in sector i in the base year (given in the SAM)
L_i^{base} is labor use in sector i in the base year (given in the SAM)
XD_i^{base} is gross production from sector i in the base year (calculated from the SAM)
C_i^{base} is consumer commodity demand in the base year (given in the SAM)
I^{base} is consumer income in the base year (given in the SAM)

For the Stone-Geary utility function, we define the Frisch parameter (which determines the money flexibility [52]): $\phi = -1.2$

Household marginal budget share of good i (rescaled such that sum over i equals one):

$$\alpha_i^h = \sigma_i^h \frac{C_i^{base}}{I^{base}} \tag{A.35}$$

Household subsistence level of good i:

$$\mu_i^h = C_i^{base} + \frac{\alpha_i^h \cdot I^{base}}{\phi} \tag{A.36}$$

Distribution factor in CES production function of firm i:

$$\gamma_i^F = 1 \Big/ \left(1 + \left(\frac{K_i}{L_i}\right)^{\frac{-1}{\sigma_i^F}}\right) \tag{A.37}$$

Efficiency parameter in CES production function of firm i:

$$a_i^F = XD_i^{base} \Bigg/ \left(\gamma_i^F \cdot K_i^{base\left(\frac{\sigma_i^F - 1}{\sigma_i^F}\right)} + \left(1 - \gamma_i^F\right) \cdot L_i^{base\left(\frac{\sigma_i^F - 1}{\sigma_i^F}\right)}\right)^{\left(\frac{\sigma_i^F}{\left(\sigma_i^F - 1\right)}\right)} \tag{A.38}$$

References

[1] Hourcade JC, Jaccard M, Bataille C, Ghersi F. Hybrid modeling: new answers to old challenges - introduction to the special issue of the Energy Journal. Energy J 2006:1–11.

[2] Grubb M, Edmonds J, ten Brink P, Morrison M. The costs of limiting fossil-fuel CO2 emissions: a Survey and Analysis. Annu Rev Energy Environ 1993;18: 397–478.

[3] Wene CO. Energy-economy analysis: linking the macroeconomic and systems engineering approaches. Energy 1996;21(9):809–24.

[4] Böhringer C, Rutherford TF. Combining bottom-up and top-down. Energy Econ 2008;30(2):574–96.

[5] Binswanger M. Technological progress and sustainable development: what about the rebound effect? Ecol Econ 2001;36(1):119–32.

[6] Shoven JB, Whalley J. Applying general equilibrium. Cambridge: Cambridge University Press; 1992.

[7] Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technologies and the cost of limiting US CO2 emissions. Energy Pol 2006;34(18):3847–69.

[8] Lanz B, Rausch S. General equilibrium, electricity generation technologies and the cost of carbon abatement: a structural sensitivity analysis. Energy Econ 2011;33(5):1035–47.

[9] Mathiesen L. Computational experience in solving equilibrium-models by a sequence of linear complementarity-problems. Oper Res 1985;33(6): 1225–50.

[10] Kehoe TJ. Multiplicity of equilibria and comparative statics*. Q J Econ 1985;100(1):119–47.

[11] Mas-Colell A. On the uniqueness of equilibrium once again. In: Barnett WA, Cornet B, D'Aspremont C, Mas-Colell A, editors. Equilibrium theory and applications: proceedings of the sixth international symposium in economic theory and econometrics. Cambridge University Press; 1991.

[12] Kehoe TJ. Uniqueness and stability. In: Kirman AP, editor. Elements of general equilibrium analysis. Wiley-Blackwell; 1998. p. 38–87.

[13] Dierker E. Two remarks on the number of equilibria of an economy. Econometrica 1972;40(5):951–3.

[14] Whalley J, Zhang SM. Tax-induced multiple equilibria. Appl Econ Lett 2011;18(13–15):1469–77.

[15] Whalley J, Zhang SM. Parametric persistence of multiple equilibria in an economy directly calibrated to 5 equilibria. Econ Model 2014;41:356–64.

[16] Mercenier J. Nonuniqueness of solutions in applied general equilibrium-models with scale economies and imperfect competition. Econ Theor 1995;6(1):161–77.

[17] Denny K, Hannan A, O'Rourke K. Fiscal increasing returns, unemployment and multiple equilibria: evidence from a computable general equilibrium model. Ireland: University College Dublin; 1997.

[18] Böhringer C, Rutherford TF. Integrated assessment of energy policies: decomposing top-down and bottom-up. J Econ Dynam Contr 2009;33(9): 1648–61.

[19] Mathiesen L. AN algorithm based on a sequence of linear complementarity-problems applied to a walrasian equilibrium-model - an example. Math Program 1987;37(1):1–18.

[20] Fortes P, Pereira R, Pereira A, Seixas J. Integrated technological-economic modeling platform for energy and climate policy analysis. Energy 2014;73:716–30.

[21] Hoffman KC, Jorgenson DW. Economic and technological models for evaluation of energy-policy. Bell J Econ 1977;8(2):444–66.

[22] Hogan WW, Weyant JP. Combined energy models. In: Moroney JR, editor. Advances in the economics of energy and resources. JAI Press; 1982.

[23] Messner S, Strubegger M. Modellsystem zur Analyse der Wechselwirkungen zwischen Energiesektor und Gesamtwirtschaft. Forschungsmemoranden. Vienna, Austria: Technical University of Vienna; 1987.

[24] Drouet L, Haurie A, Labriet M, Thalmann P, Vielle M, Viguier L. A coupled bottom-up/top-down model for ghg abatement scenarios in the swiss housing sector. In: Loulou R, Waaub J-P, Zaccour G, editors. Energy and environment. US: Springer; 2005. p. 27–61.

[25] Schafer A, Jacoby HD. Experiments with a hybrid CGE-MARKAL model. Energy J 2006:171–7.

[26] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: lessons from linking a Swedish energy system model with a CGE model. Energy 2017.

[27] Manne AS. ETA-macro: a model of energy-economy interactions. Technical report. Palo Alto, California: Electric Power Research Institute; 1977.

[28] Messner S, Schrattenholzer L. MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000;25(3):267–82.

[29] Manne A, Wene C-O. MARKAL-Macro: a linked model for energy-economy analysis. Report BNL-47161. Brookhaven National Laboratory; 1992.

[30] Bahn O, Barreto L, Kypreos S. Modelling and assessing inter-regional trade of CO2 emission reduction units. Environ Model Assess 2001;6(3):173–82.

[31] Strachan N, Kannan R. Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ 2008;30(6):2947–63.

[32] Arndt C, Davies R, Gabriel S, Makrelov K, Merven B, Hartley F, et al. A sequential approach to integrated energy modeling in South Africa. Appl Energy 2016;161:591–9.

[33] Böhringer C. The synthesis of bottom-up and top-down in energy policy modeling. Energy Econ 1998;20(3):233–48.

[34] Frei CW, Haldi PA, Sarlos G. Dynamic formulation of a top-down and bottom-up merging energy policy model. Energy Pol 2003;31(10):1017–31.

[35] Böhringer C, Löschel A. Promoting renewable energy in Europe: a hybrid computable general equilibrium approach. Energy J 2006:135–50.

[36] Scarf H, Hansen T. The computation of economic equilibria. Yale University: Yale University Press; 1973.

[37] Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Econ 2008;30(2):547–73.

[38] Proença S, St Aubyn M. Hybrid modeling to support energy-climate policy: effects of feed-in tariffs to promote renewable energy in Portugal. Energy Econ 2013;38(0):176–85.

[39] Rausch S, Mowers M. Distributional and efficiency impacts of clean and renewable energy standards for electricity. Resour Energy Econ 2014;36(2):556–85.

[40] Abrell J, Rausch S. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. JEnvironEconManage 2016;79:87–113.

[41] Bauer N, Edenhofer O, Kypreos S. Linking energy system and macroeconomic growth models. Comput Manag Sci 2008;5(1):95–117.

[42] Helgesen PI, Lind A, Ivanova O, Tomasgard A. Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport. Energy 2018;156:196–212.

[43] Barker T. The economics of avoiding dangerous climate change. An editorial essay on the Stern Review. Climatic Change 2008;89(3):173–94.

[44] Jaffe AB, Stavins RN. The energy-efficiency gap what does it mean? Energy Pol 1994;22(10):804–10.

[45] Maréchal K. The economics of climate change and the change of climate in economics. Energy Pol 2007;35(10):5181–94.

[46] Kaya A, Csala D, Sgouridis S. Constant elasticity of substitution functions for energy modeling in general equilibrium integrated assessment models: a critical review and recommendations. Climatic Change 2017;145(1):27–40.

[47] Stone JC. Formulation and solution of economic equilibrium problems. Technical Report SOL. Stanford University; 1988. p. 77.

[48] Gabriel SA, Conejo AJ, Fuller JD, Hobbs BF, Ruiz C. Complementarity modeling in energy markets. Springer; 2012.

[49] Goldberger AS, Gamaletsos T. A cross-country comparison of consumer expenditure patterns. Eur Econ Rev 1970;1(3):357–400.

[50] Lluch C. The extended linear expenditure system. Eur Econ Rev 1973;4(1):21–32.

[51] Hosoe N, Gasawa K, Hashimoto H. Textbook of computable general equilibrium modeling : programming and simulations. Palgrave Macmillan; 2010.

[52] Powell AA. Sato's insight on the relationship between the Frisch ‘parameter’ and the average elasticity of substitution. Econ Lett 1992;40(2):173–5.