Economic perspectives of market integration and demand flexibility within a smart grid dominated power sector

Økonomiske perspektiver på markedsintegrasjon og forbrukerfleksibilitet i en smart grid dominert kraftsektor

Philosophiae Doctor (PhD) Thesis

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Ås 2015

Thesis number 2015:56
ISSN 1894-6402
ISBN 978-82-575-1296-5

Table of Contents

Abstract

The developments related to integration of renewable energy sources, smart grid and market liberalization make the transition of the power system to a new state inevitable. This PhD work aims to analyze some of the market impacts associated with the important changes that will take place in the Northern European power system. First, the European countries set ambitious renewable energy targets and the share of renewable energy in the generation mix is expected to increase. Second, technological innovation has made possible the development of a smart grid that will be able to deal with the variety of new trends in the power sector. Third, the regulatory authorities in the Nordic region are cooperating on further market integration in the face of a common balance and reconciliation settlement model and a common electricity end-user market. In the course of four research articles this thesis answers questions related to the above described changes in the power sector. In particular, the PhD work describes: (i) how integration in the balance settlement procedures will impact the balancing prices; (ii) what effect a common Nordic end-user market will have on the electricity retailers' market strategies, their price markup and profit; (iii) what will be the market impacts of increased demand flexibility.

The establishment of a common Nordic balance and reconciliation settlement (NBS) model is considered an important step in the development of a common Nordic retail market. An NBS model could ease the settlement procedures, reduce the entry barriers for new participants and thus contribute to an increase in the volume of balancing bids. Based on estimated econometric relationships for historical data the PhD work discusses the impact that possible changes in the volumes of regulating bids will have on the balancing prices with the forthcoming market changes. The down-regulating price is found to be more sensitive to changes in the bids' volume than the up-regulating price. Also, the econometric model's results indicate that there are relatively large differences in the regulating prices' sensitivity to spot prices and bid volumes across different areas and seasons.

The PhD thesis discusses further the effects of a future integration of the national electricity retail markets in the Nordic region. Such a regulatory change may be expected to intensify competition among retailers. At the same time technological developments take place and these make possible the creation of a smart electricity grid where smart meters, two-way communication and real time pricing are all present. With the help of smart grid technologies, retailers will be able to significantly increase the range of their service offers, allowing customers to choose among a variety of retail products. To provide insight into the effects on competing retailers' profit, price mark-up and service level a nonlinear optimization model is formulated and solved for numerical values in the second research article included in the thesis. The results from model simulations for a two-retailer case indicate that price and service decisions made by the one retailer have strong impact on the market strategy of the other. The range of this impact depends on the overall level of price mark-up values. This topic is further elaborated on in the third research article where the nonlinear program is transformed into a mixed complementarity problem. With the help of that model the changes in the equilibrium price markup and profit for electricity retailers that are subject to specific market conditions are investigated.

Having discussed the topics of market integration and smart grid development, the focus in the PhD work is moved to the possibility of electricity demand response, enabled by smart grid functionalities and new pricing methods, to contribute with system benefits and improve the integration of variable

renewable energy in the power system. Thus, the fourth scientific article applies a detailed partial equilibrium model where within-day DR in the future Northern European power system is modeled endogenously. Out of the models' results, DR is expected to have a low impact on the average power prices and consumers' costs of electricity, to improve system balancing, and to reduce the curtailment of variable renewable energy and the short-term price variations. In general, demand response is found to provide important system benefits, while the economic benefits for the consumers are modest. Thus, increased demand flexibility could be highly beneficial during tight supply-demand situations, but consumers' response may have to be motivated by effective policy instruments.

The overall thesis' structure embraces a variety of modeling tools used to analyze the economic effects of different power system developments. Taking a leap into the future the PhD work discusses the impacts of major regulatory changes and new grid functionalities, and how these may affect actors on the power market. The capability of the thesis to provide a truthful insight into the electricity systems' developments in near future, should be considered its main research contribution.

Abstrakt

Kraftsystemet står overfor store endringer som følge av økt utbygging av fornybar energi, introduksjon av smart grid og markedsliberalisering. Dette doktorgradsarbeidet har som mål å analysere noen av de markedsmessige konsekvensene knyttet til disse viktige endringer. Forskningsarbeidet tar utgangspunkt i et smart grid dominert kraftsystem og ved hjelp av fire vitenskapelige artikler forsøker det å svare på følgende spørsmål: (i) hvordan vil bruken av en modell for felles balanseavregning påvirke balanseprisene i Norden; (ii) hvilke effekter kunne et felles nordisk sluttbrukermarked for kraft ha over kraftleverandørenes markedsstrategier, deres pris påslag og profitt; (iii) hva som kan være markedskonsekvensene av økt forbrukerfleksibilitet.

Etableringen av en felles nordisk modell for balanseavregning (NBS modell) ansees som et viktig skritt i utviklingen av et felles nordisk sluttbrukermarked for kraft. NBS modellen kunne være av hjelp for effektivisering i prosedyrene for avregning, reduserte etableringskostnader for nye aktører i balansemarkedet, og dermed kan bidra til en økning i volumet av bud for regulering. I doktorgradsarbeidet kvantifiseres de sannsynlige endringene i balanseprisene for opp- og nedregulering, som følge av en økning i regulerings bud volumet, ved hjelp av en økonometrisk estimering. Den nedregulerende prisen fremstår som mer følsom til endringer i bud volumet enn den oppregulerende prisen. Dessuten viser de økonometriske modellresultatene at det er relativt store forskjeller i de regulerende prisenes følsomhet til spot priser og bud volumer på tvers av ulike områder og årstider.

Som et neste steg beskriver avhandlingen de mulige effektene av en fremtidig integrering i de nasjonale sluttbrukermarkedene for kraft i Norden. Det kan forventes at en slik lovendring skal øke konkurransen mellom kraftleverandørene. Samtidig, den teknologiske utviklingen gjør det mulig å utvikle et smart strømnett hvor smarte målere, to-veis kommunikasjon og formidling av kraftpriser i reel tid er tilstede. Ved hjelp av smart grid teknologi skal kraftleverandørene kunne øke omfanget av deres tilbud av tjenester, slik at kundene kan velge blant en rekke kraftprodukter. I denne sammenhengen, den andre vitenskapelig artikkelen i avhandlingen gir innsikt til effektene som økt konkurranse kan ha over kraftleverandørenes profitt, pris påslag og tjenestenivå. Dette gjøres gjennom å formulere og anvende en ikke-lineær optimeringsmodell som løses for tallverdier. Resultatene fra

modellsimuleringer for en forenklet modell med to kraftleverandører tyder på at prisen og tjeneste nivået for en kraftleverandør kan ha sterk påvirkning på markedsstrategien til den andre. Denne effekten er avhengig av det overordnede pris påslag nivået. Emnet er ytterligere diskutert i en tredje vitenskapelig artikkel hvor den ikke-lineære optimeringsmodellen er omformulert til en komplementaritetsproblem. Ved hjelp av denne undersøkes kraftleverandørenes pris påslag og profitt i likevekt.

Etter å ha diskutert temaene markedsintegrering og smart grid utvikling, er fokuset i doktorgradsarbeidet flyttet til muligheten for forbrukerfleksibilitet (realisert gjennom smart grid funksjonaliteter og nye metoder for prissetting av kraftleveransen) til å gi fordeler for kraftsystemet og til å forbedre integreringen av fornybar energi. I den fjerde vitenskapelig artikkelen kommer i bruk en detaljert likevektsmodell hvor forbrukerfleksibiliteten i det fremtidige nordeuropeiske kraftsystemet er modellert endogent. Ut av modellens resultater, forventes det at forbrukerfleksibilitet skal ha liten påvirkning på de gjennomsnittlige kraftprisene og forbrukernes strømkostnader. Samtidig skal økt forbrukerfleksibilitet kunne gi en forbedret balanse i kraftsystemet, forbedret utnyttelse av kraft produsert av fornybare ressurser og lavere kortsiktige prisvariasjoner. Generelt kan bruken av forbrukerfleksibilitet bidra med viktige systemfordeler, mens de økonomiske fordelene for forbrukerne er beskjedne. Dermed kan økt forbrukerfleksibilitet være svært gunstig under vanskelig markedssituasjoner hvor etterspørsel og tilbud er i ubalanse. Likevel, kan det hende at forbrukernes respons må stimuleres gjennom effektive virkemidler.

Denne PhD avhandlingen anvender flere modelleringsmetoder for å analysere de økonomiske effektene av forskjellige utviklinger i kraftsystemet. Den gjennomførte doktorgradsarbeidet tar hensikt til fremtiden og diskuterer konsekvensene av store regulatoriske endringer og nye nett funksjonaliteter, samt hvordan disse kan påvirke aktørene i kraftmarkedet. Oppgavens evne til å gi et troverdig innsikt i kraftsystemets utvikling i nær framtid, bør vurderes dens viktigste forskningsbidrag.

Publications

Paper I:
Ilieva, I., Bolkesjø, T. F., 2014. An econometric analysis of the regulation power market at the Nordic power exchange. Energy Procedia, 58 (0): 58-64.

Paper II
Ilieva, I., Gabriel, S.A., 2014. Electricity retailers' behavior in a highly competitive Nordic electricity market. Journal of Energy Markets, 7 (4): 17-46

Paper III:
Ilieva, I., Gabriel, S.A., 2015. The impact of end-user market integration and smart grid on electricity retailers in the Nordic region. (In review – *Energy Strategy Reviews*)

Paper IV:
Tveten, Å. G., Ilieva, I., Bolkesjø, T. F., 2015. Electricity market impacts of increased demand flexibility enabled by smart grid. (In review – *The Energy Journal*)

Acknowledgements

I would like to thank…	*For…*
Torjus Folsland Bolkesjø, my main supervisor	*being always responsive, encouraging, and inspiring, and providing constructive comments and guidance.*
Bernt Bremdal, my co-supervisor	*initiating the PhD project, believing in my abilities and commenting on my work*
Steven A. Gabriel, University of Maryland	*showing me the vast possibilities of optimization research, teaching me the efficiency of the American researcher, and being of great help during the model development, analysis and revisions of our common papers*
Åsa Grytli Tveten, NMBU	*doing a great work with the Balmorel model and being a most positive and inspiring colleague*
Seksun Moryadee, University of Maryland	*the help with developing the code in GAMS*
Dieter Hirdes	*being extremely helpful and supportive, believing in me and giving me the opportunity to apply my PhD knowledge in the future*
Knut Johansen, eSmart Systems	*trusting my abilities and helping my PhD project become a reality*
Scott Hestenes, Brady Energy Norway AS	*his efforts in completing the project in tact with Brady Energy's needs and his excellent skills as a project leader*
Rita Steiner, Brady Energy Norway AS	*her efficiency in dealing with the projects' accounting*
Jo Morten Sletner, eSmart Systems	*being an extremely helpful project leader during the beginning of the project when good research questions had to be found*
Stig Ødegaard Ottesen, eSmart Systems	*his kind companionship and his positive and inspiring thoughts*
The colleagues at NCE Smart Energy Markets, Halden	*being so kind and including me in the team*
The colleagues from NMBU's renewable energy group	*the great time I had all the times I was at the university and for all the inspiring discussions and meetings*
The Norwegian Research Council, Brady Energy Norway AS and Smart Innovation Østfold	*financing my project*
Ingeborg Guldal, The Norwegian Research Council	*being always helpful and answering patiently all questions related to the project's administration*
Karsten Hedegaard, Ea Energy Analyses	*providing inspiration for my thesis' structure*
Lacho Iliev, my husband	*always showing love and support*
Stian Iliev, my son	*coming to this world and making the last two years of my PhD study the most wonderful and exhausting time in life*
My relatives in Bulgaria	*being so supportive, loving and proud of me*

List of abbreviations

BRP	Balancing responsible parties
DG	Distributed generation
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EC	The European Commission
EV	Electrical vehicles
ICT	Information and communication technologies
NBS	Nordic balance and reconciliation settlement
NordREG	Nordic Energy Regulators
NVE	Norwegian Water Resource and Energy Directorate
PPS	Purchasing power standards
RES	Renewable energy sources
RTP	Real time pricing
SR	Settlement responsible
TSO	Transmission system operator
VRE	Variable renewable energy

1. Introduction

The power sector in Northern Europe is facing a challenging task: the growing demand for electricity has to be met while ensuring sustainability. The environmental threats related to global warming comprise a major concern worldwide. The European Commission (EC) aims to reduce the power sectors' CO_2 emissions with 54 to 68% by 2030 and with 93 to 99% by 2050 (as compared to 1990) (EC 2011b). In addition to the GHG reduction targets, the European Union's strategy for sustainable growth includes increased usage of renewable energy sources (RES) in the energy mix and improved energy efficiency. These are defined as crucial, irrespective of the particular energy mix chosen (EC 2011a). In connection to the above presented sustainability measures the development of a better and highly functional electricity grid is considered most important and is among the five priorities listed in the EC's 2020 Energy Strategy (EC 2010). As acknowledged by Brown (2014), Hu et al. (2014), Muench et al. (2014), Arends and Hendriks (2014), Luthra et al. (2014), a modernized (smart) electric grid can support the integration of intermittent renewable generation (e.g., from solar and wind power) in the system and improve the efficiency related to electricity consumption and power system operation. Furthermore, technological innovation offers opportunities to improve our way of life, also with respect to the environment (Pattinson 2015). Among the key technology trends that Pattinson (2015) presents are: increased number of connected devices, increased functionality, increased demand for speed and reliability, and backward compatibility. It is the rapid development and innovation in the information and communication technologies (ICT) sector that gave life to the idea of smart grid (Usman & Shami 2013). From a power system perspective, the technology to provide for the generation, delivery and follow-up of electricity consumption is constantly improved and the ambitions of various actors to establish a smart electric grid are growing (Coll-Mayor et al. 2007).

According to the Energy Technology Platform (2010), the successful operation of an innovative power grid would require new market models with high degree of liberalization and that challenge the market actors to employ innovative technological solutions in order to stay competitive. Within the Nordic region with a well-established regional electricity exchange (Nord Pool Spot) and liberalized national end-user markets this is considered particularly important. In this regard the organization for the Nordic energy regulators (NordREG) has decided that the Nordic countries (except Iceland) should cooperate on the creation of a common Nordic model for balance settlement and the establishment of a common Nordic end-user market. Through harmonized switching procedures, common balance management and settlement system, and harmonized criteria for unbundling to ensure neutrality, a truly common Nordic retail market with free choice of supplier, will provide a high degree of competitiveness (NordREG 2014d). Competition, on its hand, can motivate retailers to innovate (Gilbert 2006) and innovative pricing contracts are a prerequisite for the successful integration of smart grid solutions (Chao 2010).

The developments related to integration of RES, smart grid and market liberalization make the transition of the power system to a new state inevitable. This PhD work aims to analyze some of the market impacts associated with the important changes that will take place in the Northern European power system. Taking a leap into the future the thesis discusses the impacts of major regulatory changes and new grid functionalities, and how these may affect actors on the power market. The capability of the PhD work to provide a truthful insight into the electricity systems' developments in near future, should be considered its main research contribution.

1.1 Changes in the power sector

1.1.1 Increased usage of RES

The expected transition in the electricity sector has drivers of various origins. The ambitious “20-20-20” targets set by the EC in 2007 (EC 2014a) have been renewed to 2030 targets (EC 2014c). The new targets include: a 40 % reduction in the GHG emissions (compared to 1990); a minimum of 27 % of the energy consumed should be based on RES; and a 30% improvement in the energy efficiency (compared to projections). As a consequence, the European Union member states should have their own national renewable energy targets that cover the period up to 2030. Table 1 below summarizes the present and the expected RES deployment for each of the countries referred to in this research work’s modeling procedures. Clearly, the share of renewable energy used will increase significantly.

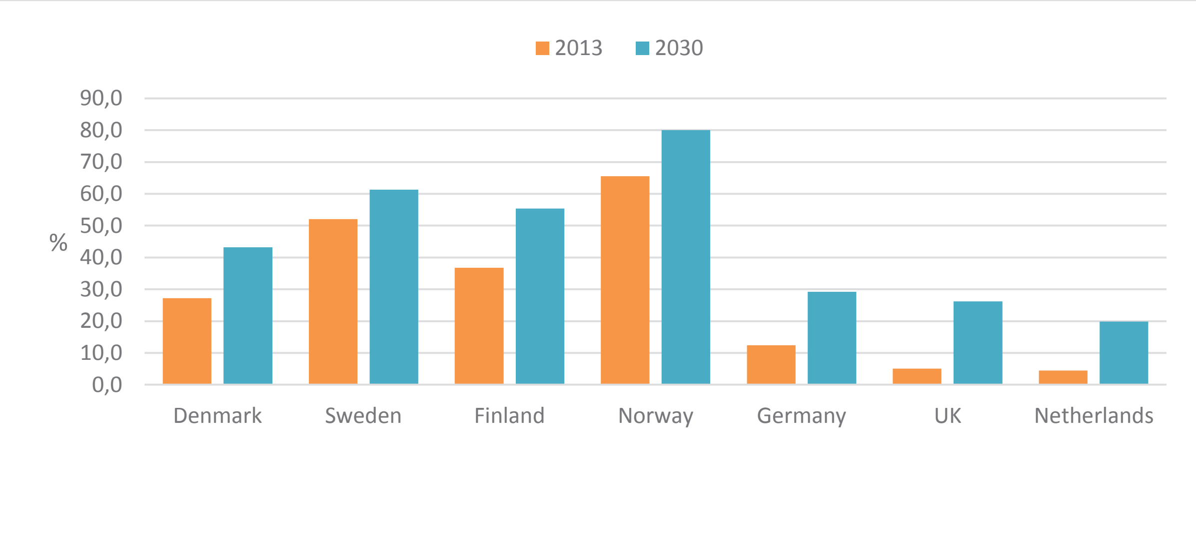

Figure 1 – Percentage share of renewable energy in the energy consumed: data for 2013 (Eurostat) and projections for 2030 based on the EC’s 2030 targets and an assumption for growing energy demand as in the EC’s Energy Roadmap 2050 (Bendiksen 2014; EC 2011a; Intelligent Energy Europe 2014)

There are different strategies to increase the deployment of RES in the power sector among the countries in Northern Europe. Denmark expects to cover 42% of its electricity consumption by wind power already in 2020 (Energinet.dk 2013). Sweden, Finland and Norway work on increasing the shares of wind, solar and hydropower in their generation mix (IEA & Nordic Energy Research 2013). In Germany the RES (wind, solar and biomass) accounted for 31% of the net electricity production for the first half of 2014 (Fraunhofer ISE 2014) and are approaching the 2020 target of 18% from gross final energy consumption. The expected 2030 generation capacity mix in Germany is to include 68% renewable energy technologies (30% wind power, 27% solar, 5% hydro and 6 % other renewable power generation technologies); and for the UK the 2030 renewable capacity projections are: 27% wind power, 18% solar, 3% hydro and 7 % other (Kringstad 2014). For the Netherlands the goal for 2020 is set to 14 % renewable energy generation as a share of final energy consumption (Dutch Ministry of Infrastructure and the Environment 2013).

The establishment of renewable energy generation facilities stimulated by government regulations, improvements in technology and reductions in their costs, is, by no doubts, making its way into the

European power system. This happens with variation in size – from small distributed generation (DG) units, to large solar power plants and off-shore wind farms, and with speed (Figure 2).

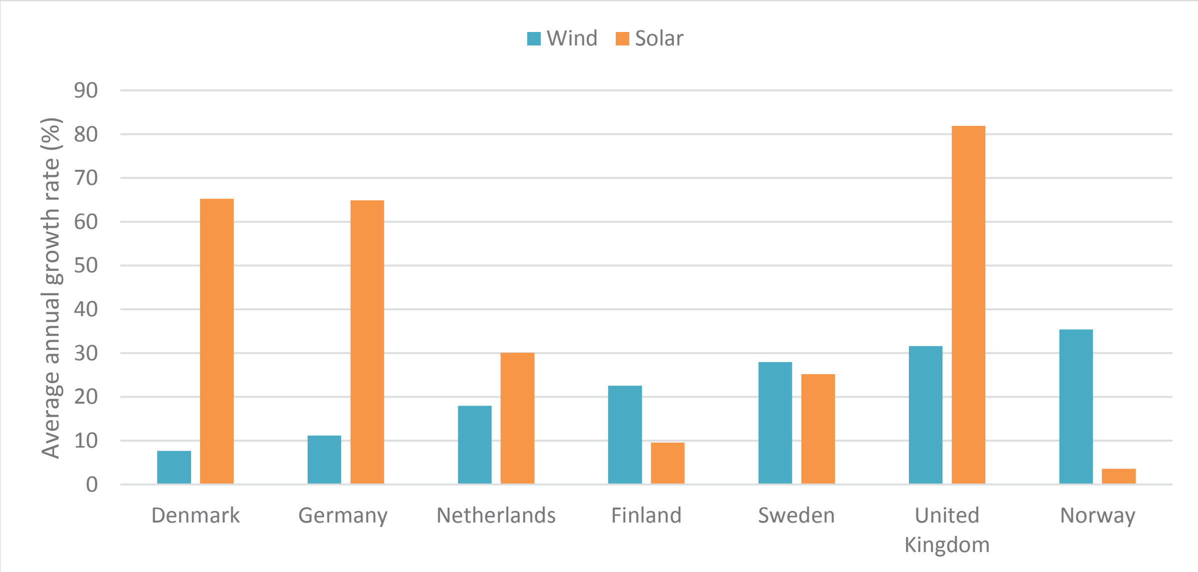

Figure 2 – Average annual growth rate for wind and solar power generation for the period 2002-2012
Data source: Worldwide electricity production from renewable energy sources, Fifteenth Inventory - Edition 2013; Statistics and figure series

The implications of high amounts renewable energy generation in the power system have been widely discussed in previous research. High shares of RES in the power generation technology mix pose challenges to the electricity grid but also provide opportunities (Chu & Majumdar 2012; Zahedi 2011). Scientists address various issues related to the integration of RES into the electricity sector. Variable renewable energies (VRE), such as wind, solar and run-of-river hydro power have huge advantage in producing carbon-free electricity. Yet, they have one main disadvantage when it comes to maintaining a reliable electricity grid and that is their intermittency (Dincer & Zamfirescu 2014; Drouineau et al. 2014). Not surprisingly, a most discussed implication related to high levels of generation based on intermittent RES has been the balancing of supply and demand. The energy system flexibility measures used to balance a system with high shares VRE in the energy mix may involve different approaches, technologies and strategies. According to Lund et al. (2015) the flexibility measures can be both on the supply and the demand side and can be classified in the following main categories: demand side management[1] (DSM), grid ancillary services, energy storage, supply side flexibility and advanced technologies such as electricity-to-thermal, power-to-gas, power-to-hydrogen, vehicle-to-grid. Challenges and opportunities related to various measures for balancing the power grid under the presence of intermittent generation are discussed, among others, in the works of Böttger et al. (2015), Droste-Franke (2015), Tarroja et al. (2015), Weitemeyer et al. (2015), Schuller and Hoeffer (2014), Stötzer et al. (2015), Stadler (2008), Rinne and Syri (2015), Bussar et al. (2014). Furthermore, Santos-Alamillos et al. (2015), Zakeri et al. (2015), Tafarte et al. (2014), Andresen et al. (2014), Heide et al. (2011) are among the authors to focus specifically on system balancing through supply side measures,

[1] Demand side management (DSM) represents a set of means that change the pattern and magnitude of electricity consumption at the end-user's premises. These may involve reduction, increase or rescheduling of electricity usage. The DSM measures can be price based (demand response (DR) in connection to, e.g., real time pricing (RTP), critical peak pricing and time-of-use pricing) or incentive based (e.g., direct load control).

or how the grid can be balanced by combining different types of renewable generation (e.g., wind and solar).

Other issues discussed in relation to the increasing generation from RES have been related to the power market. Some of the topics present in the literature are: negative prices (Brijs et al. 2015), trading mechanisms (Wang et al. 2014), market design (Chaves-Ávila & Fernandes 2015; Neuhoff et al. 2013), pricing methods (Nielsen et al. 2011). Research effort has also been directed towards the environmental and social benefits of renewable power generation - deLlano-Paz et al. (2015), Kondili and Kaldellis (2012). And last but not less important, costs and tools to facilitate the integration of renewable energy in the power sector have been discussed - Østergaard (2009), Hirth et al. (2015), Gawel and Purkus (2013), Rodriguez et al. (2015).

In this thesis the approach to RES integration is mostly concerning the challenges that they pose to grid balancing and the implications they bring to the power market (changes in the electricity prices and need for reserve capacity). While Papers I, II and III just slightly touch on the renewable power perspectives, Paper IV provides and in-depth analysis of market impacts related to high RES penetration in the energy mix and to demand response as a tool to support the grid balance.

1.1.2 Development of a smart grid

The main features of the electricity grid that we use today have remained more or less unchanged during the last century. Through transmission lines and distribution networks electricity produced by the power plants is reaching the end users, the flow of electricity is one-way and the ability to observe in detail parts of the grid is limited. And although through the years the grid has been improved as technology developed, its capability to answer the two main challenges faced by today's society – secure energy supply and reduced environmental impact, remain scarce (Orecchini & Santiangeli 2011). Among the main challenges faced by the grid are its technical ability to meet the changing electricity needs and its ability to increase its efficiency without diminishing reliability and security (Amin 2008).

In the recent years, a tremendous amount of research effort has been directed towards the development of a smart grid – a power grid that will be able to deal with the variety of new trends in the electricity sector. Politicians, power market actors, scientists and technology developers from around Europe endeavor to improve the operation of the grid and research on the components that build up the smart grid (EC 2014d). By integrating the latest ICT and advanced control technologies to the existing electricity grid, the smart grid is expected to meet the energy requirements of the 21st century in a sophisticated manner (Mahmood et al. 2015). Not surprisingly, the research and development in the smart grid field has been of significant scope and covers a wide range of technological, operational, communication, economic and regulatory aspects.

The smart grid takes in use new technologies and equipment: smart meters that allow for instantaneous measurements of electricity consumption and two-way communication between the utility and its customers, control units, sensors, IT platforms and other. Through the smart grid the currently existing producer-controlled electricity network is to transform into a less centralized and a more customer-interactive one (US DOE, 2008). The smart grid is expected to provide a wide range of opportunities (Massoud Amin 2011). The end users will be able to use electricity more efficiently by changing their electricity consumption in response to price signals or other incentives. Exercising demand flexibility on the consumer side may become an important resource for keeping the system in balance while integrating larger amounts of variable renewable energy (VRE) and may reduce the system costs associated with integration of RES (O′Connell et al. 2014). Furthermore, enabled by smart grid DSM functionalities can help for balancing a power system with increasing number of electrical vehicles (EV) (López et al. 2015). In addition, there are expectations that the smart grid may contribute for instantaneous detection and faster restoration of network failures, easier integration of micro-generation units at customers' premises, reduced operation, maintenance and investment costs for the electric utilities, and that it could bring system (and customer) benefits such as improved reliability, reduced peak demand and lower power prices (Siano 2014). Indeed, the smart grid is expected to give vast opportunities which would concern all parties related to the power system. And although the literature offers different views on the optimal smart grid model, a consensus about the essential paradigms related to smart grid deployment has been formed (Ancillotti et al. 2013): smart metering, DG, micro-grids and vehicle-to-grid technologies. In Europe a number of pilot projects have aimed to test how the different stakeholders operate given smart grid environment. An overview of more than 400 projects related to smart grid applications is provided in the Smart Grids Projects Outlook 2014 (EC 2014d).

However, there are challenges that hamper the establishment of the smart grid. These are predominantly related to regulative, cost, technological and security issues. A more detailed description is provided in part 5) of this sub-section.

1) What is the smart grid? - Definition

The smart grid has been defined in a number of peer-reviewed articles. According to Erlinghagen and Markard (2012) the smart grid is "an advanced electricity network infrastructure characterized by two-way flow of information and in many cases also a two-way flow of electricity". Muench et al. (2014) describe the smart grid as "an energy distribution system with unique features". These features are then said to allow for interaction between market participants via modern technologies, provide the capacity for smart market applications and ensure grid stability. Reddy et al. (2014) see the smart grid as a tool that "helps the power utilities to have a digital intelligence to the power system network". It comes together with "smart metering techniques, digital sensors, intelligent control systems…" and is "often referred as Energy Internet". The European Technology Platform defines the smart grid as a "an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies" and one that "employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies".

Since the birth of the smart grid concept, the smart grid has been described by various actors and for different purposes. Building further definitions should not be necessary. Yet, to elaborate on the two key components of the smart grid (smart metering and communication technologies) can be useful for understanding the analysis to follow in this research work. A more detailed description of the smart grid components is provided by Luthra et al. (2014). In addition, demand response as an important smart grid functionality and the benefits and challenges of the smart grid are discussed further below.

2) Smart meters

Smart meters are advanced electricity metering devices that not only measure consumption of electrical power, but also provide additional information (e.g., on usage and prices) and bidirectional communication (Depuru et al. 2011). Smart meters give consumers opportunity to observe their electricity consumption in real time and use electricity more efficiently. Consumers can increase or decrease their electricity demand when they face information on electricity prices and load. The extent to which consumers respond depends on their willingness to answer the price incentives, the capabilities of the smart meter and the magnitude of which automation and remote control are included (Shariatzadeh et al. 2015). The smart metering devices allow for two-way communication with the distribution system operator (DSO), or any other party that has been given access. The collected metering data can be used for monitoring and billing purposes, or to support various services provided by the utilities (Pepermans 2014). With the help of smart meters it becomes easier for the electricity utilities to detect system failures, carry on billing and balancing procedures and communicate with the end user (McHenry 2013). Consequently, their operational costs can be lowered.

For Norway the Norwegian Water Resource and Energy Directorate (NVE) has set the target of full smart metering coverage in the country by 2017 (NVE 2012). And for most EU member states a smart metering roll-out penetration rate of 80% is required by 2020 (EC 2014b).

3) Technology for communication and automation

The development in the ICT can be seen as the basis for a smart grid transformation in the power sector. The technology parts needed to build the smart grid are already available (Usman & Shami 2013) and the challenging task is to successfully integrate the ICT into the energy system. In the smart grid all actors should be able to communicate efficiently with their counterparts, and eventually the communication processes should be carried out automatically, or with as little manual interference as possible (Wissner 2011). As Wissner (2011) indicates the functionalities of ICT can support the operation of various market actors in different ways: assist electricity producers in the integration of intermittent generation and in the establishment of virtual power plants[2]; support the transmission system operator (TSO) in providing reserve power in a most efficient way; help DSOs in carrying DSM programs; allow the end-users to effectively steer their consumption and benefit from automated operations in smart houses/intelligent buildings.

Nevertheless, the issues related to investment in smart grid technology represent the most frequently cited pitfall of smart grid implementation and include risk, expense and availability of capital (Xenias et al. 2015). In addition, smart grid deployment may require larger amounts of capital in a relatively short period, which, considered the risk of facing unresponsive or uncooperative customers within a relatively complex network of customer-utility relationships, may have negative impact on investments. For the above reasons, smart grid deployment happens slowly and cautiously, and is subject to numerous tests and projects (e.g., those presented by EC (2014d)) In general, the countries are searching for the best practices to make the grid efficient at least cost and there is skepticism in taking too hasty decisions.

4) Demand response

Demand response, or the change in electricity usage pattern in response to prices, is one of the most discussed smart grid related issues. The ability of DR to assist in balancing supply and demand by following electricity price signals makes it an important resource in both system and market operation (Magnago et al. 2015). The possibility to balance the system through DR becomes more valuable as

[2] A virtual power plant represents a combination of smaller generation units, often based on intermittent renewable power.

the shares of power generated from intermittent RES increase. As demonstrated by Bouckaert et al. (2014), DR solutions can counteract the decreasing system reliability associated with high shares RES in the generation mix. An in-depth discussion on the DR topic (definitions, classification, benefit and cost assessment, measurement, price effects and literature) is provided in the work of Aghaei and Alizadeh (2013).

The two-way communication functionality provided by the smart grid gives end-users the possibility to respond to price signals. Consequently, demand response can be considered an asset for the electricity retailers' business. The challenges that electricity retailers face when dealing with demand response are related to the integration of a variety of new pricing methods and customer programs and the associated costs for the retailers. The programs have to be mindfully chosen and practiced with caution to ensure customers' response and to realize system and economic benefits to a highest possible degree (Mahmoudi et al. 2014a). With sufficient customer knowledge in place, the price incentives, charging methods and programs that retailers offer may have strong impact on electricity usage (Geelen et al. 2013). In the literature researchers have used different approaches to address the impact of DR on electricity retailers' practices (Hatami et al. 2009a; Horowitz & Woo 2006; Mahmoudi et al. 2014a; Yang et al. 2014; Yousefi et al. 2011; Zhong et al. 2013). However, the available research works do not provide a single answer on how retailers should deal with demand flexibility on the end-users' side, but rather suggest and compare different approaches. In addition, retailers should consider the costs related to using DR programs, which, given the uncertain customer response, may be a barrier to implementing DR measures.

5) Smart grid benefits and challenges

The smart grid has innovation and technology in its core and its purpose is to deliver various benefits to the power system. Tekiner-Mogulkoc et al. (2012) summarize the benefits of smart grid technologies in three main categories: shift/reduction in energy demand, increased effective availability of the system components, reduced energy losses related to transmission and distribution. According to Dada (2014) the smart grid contributes to the power system through improved reliability and efficiency, financial and environmental benefits, and strengthened security and safety. However, the range of stakeholder-specific benefits related to smart grid is much wider. Some important potential benefits for the current users of the power grid – electricity producers, retailers, distributors, TSOs and end-users, have been presented by Siano (2014). Using Siano's work as a reference the expected benefits have been summarized in Table 1 below. The degree to which the benefits become realized (given that technological and regulatory barriers are overcome) will, of course, depend on the level of knowledge on smart grid attained by end-users, on their willingness to participate in DR programs and their customer engagement (Honebein et al. 2011).

Table 1 – Potential benefits of smart grid

Electricity producers	Reduced energy production in peak hours Avoided investments in peak units Reduced requirements for capacity reserves and operating reserves Increased reliability of supply Improved balancing Reduced energy costs Reduced emissions
Electricity retailers	Improved billing and settlement procedures

Electricity retailers	Reduced risk of imbalances Reduced volatility in power prices Possibility to offer innovative contracts to consumers Possibility to provide customers with wider choice of power products and services
Electricity distributors	Improved metering and operation Increased efficiency through real time data usage Decreased need for investments in distribution network Increased network reliability Easier detection of system failures Reduced network losses
Transmission system operators	Improved operation Decreased need for investments in transmission network Increased network reliability Avoided outages
End users	More choice to satisfy preferences A contract regime that is better customized for their own situation Increased flexibility related to change in prices Contribute to environmental benefits

The challenges related to smart grid can be as numerous as its benefits. The main challenges discussed in previous literature are summarized hereby. First, there are technological issues that have to be overcome. As acknowledged by Mouftah and Erol-Kantarci (2013), the communication standards for smart grid are not mature and the existing wired and wireless communication technologies face hardships to integrate in the future smart grid. The technological challenges associated with smart grid development have been discussed, among others, in the works of Donohoe et al. (2015), Massoud Amin (2011), Ancillotti et al. (2013). Besides, research effort has been directed specifically towards the cyber security issues within a smart grid environment (Elmaghraby & Losavio 2014; Ericsson 2010; Pearson 2011; Wang & Lu 2013). Second, the costs associated with implementing smart grid activities may be significant and have a restrictive impact on a large scale deployment. Cost benefit analysis for smart grid deployment has been applied in the studies of, among others, Faruqui et al. (2010), Jackson (2011), De Castro and Dutra (2013). In general, the literature provides a detailed description of the various smart grid related benefits and costs and shows that these are often not straightforward and it may be a challenging task to define them in money terms and split among market actors. As an example, regulators may be focusing on the electricity prices while not considering the efficiency and reliability impacts that are hard to quantify. Furthermore, in some cases, there might be a mismatch between the market actor to accrue the benefits and the one to bear the costs (Hall & Foxon 2014). Finally, as noted by Colak et al. (2015), the successful development of smart grid is heavily dependent on a set of conditions, such as innovative regulatory and legislative agreements, sufficient consumer engagement and acceptance, technology advances, interoperability and industrial standards.

1.1.3 Market integration

The authorities in the Nordic countries have long been cooperating on market integration within the Nordic power sector and the well-functioning electricity market – The Nordic power exchange Nord Pool Spot, established in 1996, is a proof for that. In recent years the efforts for further market integration and harmonization in the Nordic region have moved to a next level. The regulating authorities have decided to take two big steps on the road to market integration. The first concerns the balancing power market which is a part of the Nord Pool market. The Finnish, Norwegian and Swedish TSOs (Fingrid Oyj, Statnett and Svenska Kraftnät) have agreed in 2010 to establish a common model for balance and reconciliation settlement (NBS model). The NBS model is planned to provide similar operating conditions for all balance responsible parties (BRP)[3], despite their area and country (Statnett et al. 2012). Furthermore, the NBS model will outsource the operative management of balance settlement to a separate inter-Nordic balance settlement unit referred to as Settlement Responsible (SR) (Fingrid 2011). A decision has been taken in 2012 that the SR unit will be established in Finland (NBS 2012). In addition, the new model for balance settlement is to create common rules and standards for data exchange and contribute to a number of benefits in the Nordic power market (Svenska Kraftnät et al. 2011). The NBS model is expected to become operational in 2016. This first regulatory change – the NBS model - should serve as a facilitator for the second one - the establishment of a common Nordic retail market for electricity.

The Nordic Energy Regulators (NordREG) have since 2008 been working to create a common Nordic[4] end-user market for electricity with the purpose to further harmonize the market and ensure its high level of competitiveness . Through increased number of electricity retailers to operate across larger market territories, the common electricity end-user market[5] is expected to boost competition and stimulate electricity retailers to offer innovative services (e.g., such that take in use the many opportunities provided by the smart grid) (NordREG 2014a). Within a common Nordic electricity retail market all electricity customers will enjoy free choice of supplier, efficient and competitive prices and will be guaranteed reliable supply through the internal Nordic and European electricity market (NordREG 2009). The common Nordic electricity end-user market is to ensure that suppliers[6] can operate without any significant regulatory or technical obstacles in all of the Nordic countries (except in Iceland which is not part of the common market model). Thus, harmonization activities have been required: e.g., harmonizing the legal frameworks, harmonizing the switching procedures, etc. Denmark and Norway are even developing data hubs that are to collect all the metering data and make it accessible for electricity retailers, end users and third parties. The data hubs can thus contribute for adding efficiency to the retail market structures and offering better and more innovative services to the end-user (Elhub 2014). Finally, it is important to note that the Nordic market is being increasingly connected to the Continent – both through more interconnector capacities and their efficient utilization. Therefore, optimal market operation within the Nordic region would be of importance for the European power sector as a whole.

2. The research topics and related work

2.1 Goals and research question

The research work presented here aims to elaborate on the economic impacts of the above discussed three important changes that the Nordic power system is to inevitably go through: increased penetration of RES, market integration, and development of smart grid infrastructure that enables

[3] Balance responsible parties are considered those power market actors that have agreements with the system operator to buy or sell market power in order to neutralize grid imbalances.
[4] The countries to participate in the common Nordic end-user market are Norway, Finland, Sweden and Denmark.
[5] In this work the terms end-user market and retail market are used interchangeably.
[6] In this work the terms retailers and suppliers are used interchangeably.

utilizing demand flexibility. In this regard, the PhD project, part of the industrial PhD program of the Norwegian Research Council, has the following goals:

1. *Contribute to the decision-making processes within the company responsible for the project by describing probable market impacts of regulatory and technological changes.*
2. *Provide a scientific contribution to the field of energy system analysis by applying different modeling tools to define and quantify these impacts.*

In general, the work presented in this PhD thesis is meant to answer the following research question:

- *In the presence of a smart grid environment - what could be the economic effects of market integration and increased demand flexibility on the balancing and end-user markets, and on a power system with high VRE shares in the energy mix?*

The results and analysis presented in this PhD work should be useful for companies operating in smart grid dominated market environment by helping them in developing good market strategies and prioritizing investments. In addition, the PhD thesis may provide helpful input to policy makers when deciding on future market rules and regulations. The variety of modeling approaches applied in this thesis' framework can be of use to researchers and other professionals working with power market analysis and models.

The thesis focuses on several changes that are to take place in the power system: common NBS model for Norway, Finland and Sweden; common Nordic end-user market for electricity; increased use of RES in the generation mix; increased penetration of smart grid technologies in the power system (that will also allow for increased flexibility on the demand side). The economic effects of these changes have been evaluated in terms of elasticity in the balancing prices (Paper I), electricity retailers' price markups and profits (Papers II and III), average electricity prices, variations in demand and costs for electricity consumers (Paper IV). In addition, the possibility of DR to reduce the need for peak power technologies and improve the integration of VRE, and the consequent impact on GHG emissions have been investigated (Paper IV).

2.2 Overview of papers

This thesis includes four papers which apply different modeling procedures. An overview is provided in Table 2 below.

Table 2 – Overview of scientific articles to build up the thesis

Paper	Main focus	Type of method/model used
Paper I	The impact of increasing volumes of regulating bids (a possible consequence of an NBS model) on the balancing prices	Econometric modelling
Paper II	The common Nordic end-user market and its impact on electricity retailers	Nonlinear optimization model
Paper III	The common Nordic end-user market and its impact on electricity retailers	Mixed complementarity problem and econometric estimation
Paper IV	The impact of DR in a power system with increasing shares of VRE	Linear partial equilibrium model

As it can be seen in Table 2, Papers II and III are close in their focus, while Papers I and IV are with different topics. Yet, the issues discussed in all four papers are connected in the aim to jointly provide a thorough representation of the important changes that are to take place within the Northern European power system. The methodology used in each paper is different and reflects the need of variety in the modeling tools when analyzing complex systems, such as the power system.

Paper I, "An econometric analysis of the regulation power market at the Nordic power exchange" investigates the possible adjustments in the balancing prices that may take place in an NBS regime. In particular, the paper analyzes how the regulating prices in the different price areas of the Nord Pool region are affected by the level of the spot price and the volumes of the regulating bids. With the help of an econometric model the sensitivity of up- and down-regulating prices with respect to the volumes of regulating bids is quantified.

Paper II, "Electricity retailers' behavior in a highly competitive Nordic electricity market" focuses on the likely effects a pending regulatory change to a common Nordic end-user market, based on the functionalities offered by smart metering. Specifically, the effects on competing retailers' profit, price markup and service investments are investigated. In paper II a nonlinear program is formulated and solved for a two-retailer case. The results from several model simulations indicate how the price and service decisions of one retailer may impact the market strategies of the other.

Paper III, "The impact of end-user market integration and smart grid on electricity retailers in the Nordic region", keeps the focus on the end-user market, but the model from Paper II is being transformed to a mixed complementarity problem. The transformed model is used to analyze the impact of market integration on electricity retailers' price markup and profit within a smart grid dominated power system. And while Paper II describes the outcomes for each retailer, Paper III reflects on the equilibrium price markup and profit values.

Paper IV, "Electricity market impacts of increased demand flexibility enabled by smart grid" analyzes the market effects of increased DR in terms of reduced need for peak power technologies, changing electricity prices, GHG emissions, residual demand and consumers' cost of electricity. With the help of a detailed partial equilibrium model representing the Northern European power system, the paper describes the possible impacts of DR within a future power market framework. While Papers I, II and III just slightly touch on RES penetration, in Paper IV the possibility of DR to improve the integration of large-scale VRE is a key issue.

2.3 Previous studies

The topics related to Papers I-IV have been discussed in previous literature. This section reviews previous literature within the specific fields, and sets into its context the research conducted in this PhD study. A more detailed literature review can be found in each paper's review section.

2.3.1 Market integration

Integration of the electricity retail markets in the Nordic region has been analyzed by Amundsen and Bergman (2007), Olsen et al. (2006), Littlechild (2006). These works indicate some of the obstacles for an integrated and better functioning retail market – such as limited information on contracts and prices, metering issues, differences in the national electricity markets' legislation and uncertainty of the wholesale prices. Also, as Olsen et al. (2006) argue, besides the technical and administrative barriers on the road to Nordic retail market integration, there are the specific to each country balancing requirements that hamper competition. The existing literature on integration of the balancing market procedures is, however, of limited scope. It has been mostly directed towards the operational challenges associated with accommodating VRE in the system (Sorknæs et al. 2013; Vandezande et al. 2010), the development of a larger in size regulating market (Farahmand et al. 2012; Farahmand & Doorman 2012; Jaehnert & Doorman 2012), or towards the connection of micro-generation (Van der Veen & De Vries 2009). The first research paper, part of this PhD study, investigates the effects that a common settlement model may have on the balancing prices. The Nordic energy regulators consider the NBS model a necessary step towards a successfully operating common Nordic end-user market. Thus, the establishment of common settlement model is an important change and is worth research attention. Paper I uses similar econometric specification as Skytte (1999) and in both studies the impacts on the regulating prices are investigated. However, the approach of Paper I differs from Skytte (1999) in the drivers causing the price changes: in Skytte (1999) these are the costs associated with the inability of market actors to meet the commitments made at the power exchange, while in Paper I the changing bid volumes (caused by implementing the NBS model) are used.

In the recent years the Nordic energy authorities have worked on overcoming the main obstacles to further market integration (NordREG 2012). The transition to a common Nordic electricity retail market, with a preceding establishment of an NBS model, is expected to take place in 2018 at latest. To understand the benefits and impacts of retail market integration it is of help to look at the behavior and optimization strategies of electricity retailers. These issues are discussed by, e.g.: Charwand and Moshavash (2014); Gabriel et al. (2002); Gabriel et al. (2004); Gabriel et al. (2006); Hatami et al. (2009b); Yusta et al. (2005); Zugno et al. (2013). These papers use advanced modelling procedures to draw conclusions about electricity retailers' market strategies, specifically related to pricing and retail contracts. Other scientific articles - Mahmoudi et al. (2014a), Mahmoudi et al. (2014b), focus on the opportunities for utilizing demand response in retailers' business and the associated challenges. Bae et al. (2014) connect the issues of market integration and smart grid infrastructure in a single research work. They discuss electricity retail competition in the light of new business models, smart metering standards and privacy-security issues. Yet, none of the existing literature contributions considers the retailers' behavior related to a "price against service" decision making. To offer sufficient level of smart grid related services (such as energy management programs, including management of flexible load, distributed generation and EV charging, and new power-pricing schemes) might become an important part of the electricity retailers' business in a smart grid dominated power system. Paper II in this PhD study considers a market setting where electricity retailers' price and service decisions are the main competition tools. In Paper II service has been defined through a proxy variable that reflects the average investment in service, and is integrated in a model that applies an hourly resolution in the simulation procedures. Characterized by the above described features the second paper represents a novel approach in the literature on electricity retail competition.

Paper III discusses further the impacts of end-user market integration on electricity retailers. For the purpose the model used in Paper II is being transformed into a complementarity problem. Applying game theory, Paper III investigates the combinations of equilibrium retail price markups and profits under different market scenarios. Complementarity based power market models have been applied in the power market related literature for different purposes: describing producers' optimal strategies (Bushnell 2003; Rivier et al. 2001; Ruiz et al. 2013; Singh 1999) or optimizing simultaneously the behavior of different market actors – producers, consumers, retailers, distributors (Hobbs & Helman 2004; Ralph & Smeers 2006). However, the use of mixed complementarity models to represent the behavior of electricity retailers alone has been limited. The lack of deregulation in the end-user markets in many countries could be one reason for that. As acknowledged by Joskow (2008), the Nordic market is among the few ones to be most successful in stimulating trade in retail services. Thus, the modeling approach in combination with the Nordic power market data used should present a valuable contribution to research in the field.

2.3.2 Demand response and integration of RES

Demand response is considered an important resource for the electricity system (Muratori et al. 2014). Without flexibility on the demand side the spot prices are determined by the availability of electricity generation technologies and the pricing of their production for a given consumption level. During situations where some supply units are out of operation, or there is a limited/uncertain access to generation resources (as it is often the case with VRE), it might become necessary for more expensive and polluting generation to be taken into use, which may lead to higher prices and more GHG emissions. Also the security of electricity supply may be threatened. A situation with high electricity demand and limited supply may result in increased market prices as well. Change in the electricity consumption pattern can help to cope with these challenges. Claims that flexible electricity consumption could be a good tool for avoiding stringent situations and ensuring an efficient use of resources are present in, among others, the works of O'Connell et al. (2014), Powells et al. (2014), Shen et al. (2014), Bergaentzlé et al. (2014), Strbac (2008), Bradley et al. (2013).

Consumers could exercise DR when being exposed to the electricity spot prices coming from the electricity spot market. If consumers use less electricity when the market prices are high they can lower their bills and extreme situations with too high prices can be prevented (Magnago et al. 2015). Flexible electricity consumption could contribute to other benefits as well. It can improve the reliability during situations where bottlenecks threaten the security of the system. In the best case the need for grid capacity investments could be prevented if a stable and sufficient level of demand flexibility is present (Poudineh & Jamasb 2014). Also, as DR is capable of reducing the peak load (Gyamfi & Krumdieck 2012), the need for peak power capacity could be reduced and the volatility of power prices decreased. In this regard, DR can work in an environmentally friendly manner as well, as the need for starting peak power capacities that typically run on fossil fuels will be reduced. The various benefits of DR are discussed by, e.g., Albadi and El-Saadany (2008), O'Connell et al. (2014), Siano (2014).

Yet, among the most advantageous qualities of DR is its ability to assist in balancing the power system given a large-scale penetration of RES. This topic has been discussed, among others, in the works of: Aghaei and Alizadeh (2013); Dupont et al. (2014); Finn and Fitzpatrick (2014b); Stadler (2008). Also, as acknowledged by Savolainen and Svento (2012), demand response programs based on RTP can reduce the need for generation capacity and promote market access of renewables. However, the number of peer-reviewed articles to discuss the market effects of DR on heterogeneous power systems has been limited (Göransson et al. 2014). Paper IV focuses on the effect of DR for VRE integration and improved VRE market value – issues which, as noted by Hirth (2015), have not been addressed by many previous studies at a market scale. Paper IV contributes to the existing DR related literature by emphasizing on the mixed effect for the different generation technologies, the rather limited benefits for the consumers, and the likely larger benefits for the energy system. In addition, the paper includes a thorough analysis of how the most important energy system assumptions influence the effect of DR, thus increasing the understanding of the results' generality. The novelty of Paper IV from a methodological viewpoint is discussed in Section 4.2.4.

3. Theoretical framework

This chapter describes the markets that Papers I-IV focus on. First, the features of the balancing market are discussed. Next, the focus is set on the electricity retail market and the market strategies of the suppliers. Finally, key issues related to demand response, integration of RES and power system impacts are presented. Although the separate topics may seem distanced from each other, they are related in the sense of their joint contribution to the future power system and the role that market actors will have in it.

3.1 Power balancing

Keeping supply and demand in balance is critical for the power system. But despite the fact that supply and demand are equalized when clearing the planned quantities at the power exchange, imbalances can still occur. These can be a consequence of, e.g., network outages, failure to generate according to the plans, forecasting errors for VRE generation technologies or an unexpected change in consumption. To compensate for the imbalances the power system should possess enough reserve capacity. Trading the reserve capacities on a balancing power market ensures that the cheapest available resource is utilized and that system balancing is carried in a most efficient way.

Electricity retailers buy power at the market based on estimates on how much electricity their clients will consume. If the estimated figures deviate from the actual ones they should either per definition sell excess power to the system operator (in the case when customers have used less than expected) or buy power from the system operator (when customers have used more than expected). This deviating amount of electricity that is to be settled between the TSOs and retailers represents the balancing power (Nord Pool Spot 2011).

Balancing power needs also to be settled between producers and TSOs when producers fail to produce according to the plans (the offers given at Nord Pool Spot the day before delivery). To define the price for this settlement, however, it is important to distinguish between hours for up-regulation when more electricity needs to be produced, and hours of down-regulation when more than necessary power is being generated. Under the up-regulating hours the units producing more than settled in the day ahead market will only get paid the market price, while those producing less than settled will be invoiced a price that is normally higher than the market – the up-regulating price. The situation is different during hours with down-regulation. Then the utilities producing more than settled in the day ahead market will get paid a price typically lower than the market – the down-regulating price, and those producing less than settled will be invoiced the market price (Nord Pool Spot 2011). It should be noted that balancing power is settled only between the market actors and the TSOs. Thus, if a producer fails to produce the contracted with a retailer quantity of power to be delivered, it still gets paid the contracted amount by the retailer. Balancing power is then settled between the producer and the TSO (Nord Pool Spot 2011). This means that payments at the spot and regulating markets are independently made. Figure 3 illustrates price setting in the balancing market and a case where 500MW of down-regulation are needed. The price of the last down-regulating MW to be taken in use defines the price of down-regulation. All parties to offer balancing power below this price make profit equal to the difference between the down-regulation price and the price they have offered.

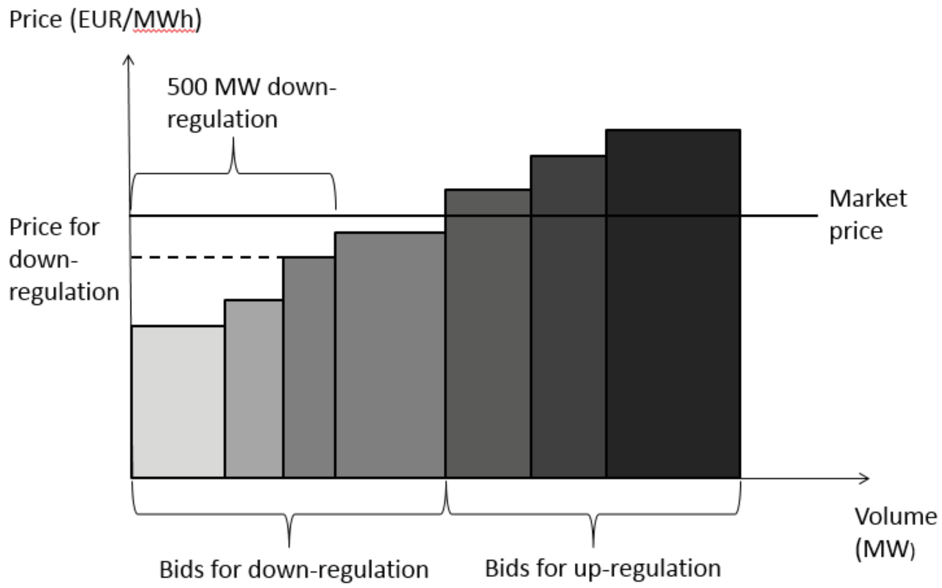

Figure 3 – Price setting in the balancing power market

The operation of a balancing market helps producers that have difficulties to fulfill their commitments to the spot market but have no flexibility in generation to meet market actors which can rapidly regulate their production. This happens through the market mechanism with up- and down-regulating prices and helps keeping the balance between supply and demand in real time.

For electricity retailers the balance settlement ensures that power can be sold back or bought in the case of inaccurate estimates of customers' consumption. Buyers could also make profit getting paid to decrease their consumption during hours with up-regulation. For the TSOs the balancing market is an effective instrument to ensure that balance in the system is provided at a low cost. As seen in Figure 3, the bids with lowest price for down-regulation are activated when less power generation is needed. Without the existence of an integrated Nordic market for balancing services there would be less competition for efficient use of balancing resources within national control areas. Enabling competition between producers of regulating power the Nordic regulating power market helps solving the balancing problem in an economically optimal way – the balancing market mechanism ensures that up and down regulation will be taken care of by the least costly resources, irrespective of which Nordic country they are situated in.

Referring to the above described features, the regulating market could be defined as a specific commodity market where regulating power serves the concrete need to keep the power system in balance. This market is subject to distinct institutional and legal settings with an underlying goal to provide for an efficient grid balance at a lowest cost. Additional internationalization of this market – in the form of an NBS model – is expected to make trade with balancing power easier and will likely contribute for a better utilization of the balancing resources.

3.1.1 The NBS model – a step towards further market integration

Cross-border balancing has been used in the Nordic market area since 2002 (NordREG 2010). The market model used relies on cooperation between the TSOs and is referred to as a "TSO-to-TSO model with common merit order" (NordREG 2010). This means that a common merit order list with balancing capacity offered for either up- or down-regulation is maintained visible to all TSOs. In this way, the least costly resources can be utilized for balancing services, disregarding their location in the Nordic power system, of course, subject to the available transmission capacity. Under the settlement procedures the settlement of imbalances between the countries takes place first, and then imbalance settlement within each country is carried on. Each country's system operator is responsible for settling the balancing power used no matter if it comes from another Nordic country or from a local producer.

Cross-border trade with balancing power requires high level of cooperation between TSOs and high level of transparency. And these needs gain importance with the increasing share of intermittent generation in the Nordic region (NordREG 2010). Harmonization of rules applied in the balancing procedures is thus seen as a key driver towards increased cooperation and effective market integration of RES.

As described earlier in Section 1.1.3, the Swedish, Finnish and Norwegian TSOs cooperate to create a harmonized model for balance settlement, which is expected to be completed by 2016 (Statnett et al. 2012). The main goals that stand behind this project are several. First, a harmonized model would help provide similar conditions for operation to all BRPs and ease participation (currently there are different principles for settlement and different standards in the Nordic countries). As a result, competition among BRPs will increase and costs for retailers and producers will be lowered. Second, a successive implementation of the NBS model is expected to increase transparency and innovation, as well as the quality of settlement and invoicing. And third, common rules and standards for data exchange would allow for easier information exchange among balancing market actors in the different countries (Statnett et al. 2012). All these features are expected to contribute for further Nordic power market integration in the form of a common Nordic retail market.

As a consequence of the harmonization in the balance settlement procedures it may be expected that more market actors will be willing to offer reserve capacity at the regulating power market and the bid volumes might increase. Besides, more balancing power may be needed given the increasing shares of VRE in the system. Thus, it is of interest to investigate what effect the larger bid volumes may have on the prices for up and down regulation, also with respect to the generation mix in the separate country and to seasonal variations. This topic is discussed in Paper I.

3.2 Electricity retail

During the past decades market integration resolutions within the Nordic power sector have mainly concerned the electricity wholesale market. Since 1996 the Nordic power exchange Nord Pool has been developed and represents one of the best examples of an international electricity market in the world (NordREG 2009). The participants in the power exchange - electricity generators and retailers, are being able to benefit from the opportunities offered by an integrated market and, as per 2014, there were 380 companies from 20 countries trading in it (Nord Pool Spot 2015).

Despite the high level of integration of the electricity wholesale sectors in the Nordic countries, electricity retail has so far been restricted within each country's boundary. The creation of a common Nordic end-user market is thus considered a next natural step to electricity market integration (NordREG 2009). Within a common end-user market it will be possible for electricity retailers to operate independently of their country of origin and the consumers will be given the possibility to choose supplier freely and thus indirectly take part in the Nordic power exchange. This change is to be in tact with economic theory that describes a well-functioning electricity market as one in which the customers are active and well informed, and choose the most competitive suppliers and contracts (NVE 2014).

However, the level of market power is specifically important in the context of free competition, and hereby the situation in Norway[7] for 2014 will be briefly described. The average market share of the dominating electricity retailers in each of Norway's grid areas for 2014 has been 71%. This high number indicates that most customers are loyal to the incumbent companies and suggests that competitiveness at the retail market and customers' engagement are rather low. Yet, the market share of the dominating retailer has been gradually decreasing since the deregulation in the Norwegian retail market in 1997 (before which the retailers were monopolies in the local grid area), and has been dropping by on average 1% per year since 2010 (NVE 2015). Thus, retail market power seems to be on an, albeit slow, downturn and this should have positive meaning for the integration of the Nordic retail markets.

As part of the harmonization towards a common Nordic retail market, NordREG has proposed the development of a more supplier-centric model. Such model is to be characterized with the retailer being responsible for invoicing both electricity supply and distribution, and for offering customer assistance. The DSO remains in responsibility for grid maintenance, connecting to the grid and disconnecting. Under such market model the customers are to a highest possible degree in interaction with the suppliers and the role of electricity suppliers in the market is expected to become increasingly important.

The national electricity end-user markets of the Nordic countries have been liberalized for over two decades. The number of supplier switches has been varying over the years and currently remains within the interval of 7 to 15% (Figure 4 and Table 3).

Table 3 – Key statistics for the internal retail markets in the Nordic region:

	Denmark	**Finland**	**Norway**	**Sweden**
Year of liberalization	2003	1997	1991	2003
Switch rate	7%	10%	15%	11%
Number of suppliers	53	74	99	121
Share of suppliers covering the whole market	58%	43%	28%	81%

Data source: NordREG (2014b); NordREG (2014c)

[7] The Norwegian retail market is the one for which data is being used to carry on the analysis in Papers II and III.

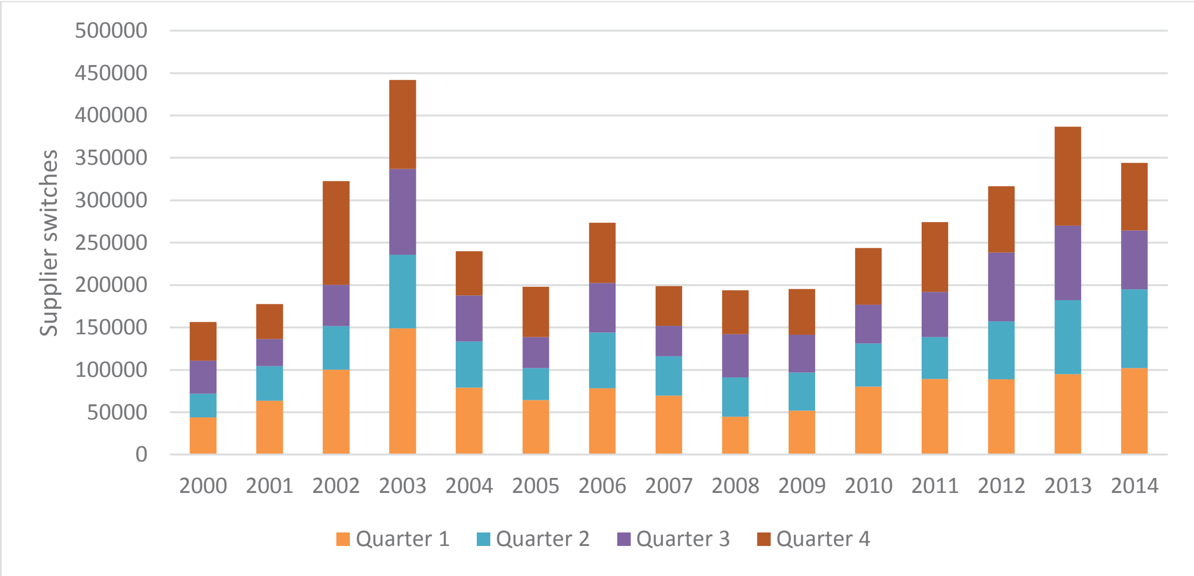

Figure 4 – Number of supplier switches in Norway for the period 2000-2014 (quarterly).
Data source: NVE

As Table 3 indicates the percentage share of supplier switches is higher for Norway which is also the Nordic country with the longest liberalization history. Yet, as shown in Figure 4, the number of supplier switches has been changing. In 2002/2003 there has been observed a considerable increase in the number supplier switches. These peaks correspond to periods with high electricity prices. But the electricity price is just one of customers' stimuli to change suppliers. Other important factors in this respect should be considered customer preferences and satisfaction (NordREG 2014b). Also, for most of the years presented in Figure 4, the number of switches is higher for the first and the fourth quarter, suggesting that customers have increased willingness to switch during the cold months of the year when consumption level and electricity prices are typically higher. In general, the graphical representation in Figure 4 indicates increase in the supplier switches since 2009, independently of price spikes. This might be an indicator of consumers' increasing knowledge and interest in electricity retail offers.

A common Nordic end-user market solution will increase the number of retailers that customers can choose among and competition will be intensified. The current switching rates indicate that end-users can actively participate in the market. And this trend may be expected to persist as customers' knowledge on retail offers increases. However, end-user prices in the Nordic countries (except for Denmark due to high taxes) are relatively low. Figure 5 represents the end-user prices for electricity for the European countries calculated as purchasing power standards (PPS) – an artificial reference currency that is used to eliminate the differences in price level between countries.

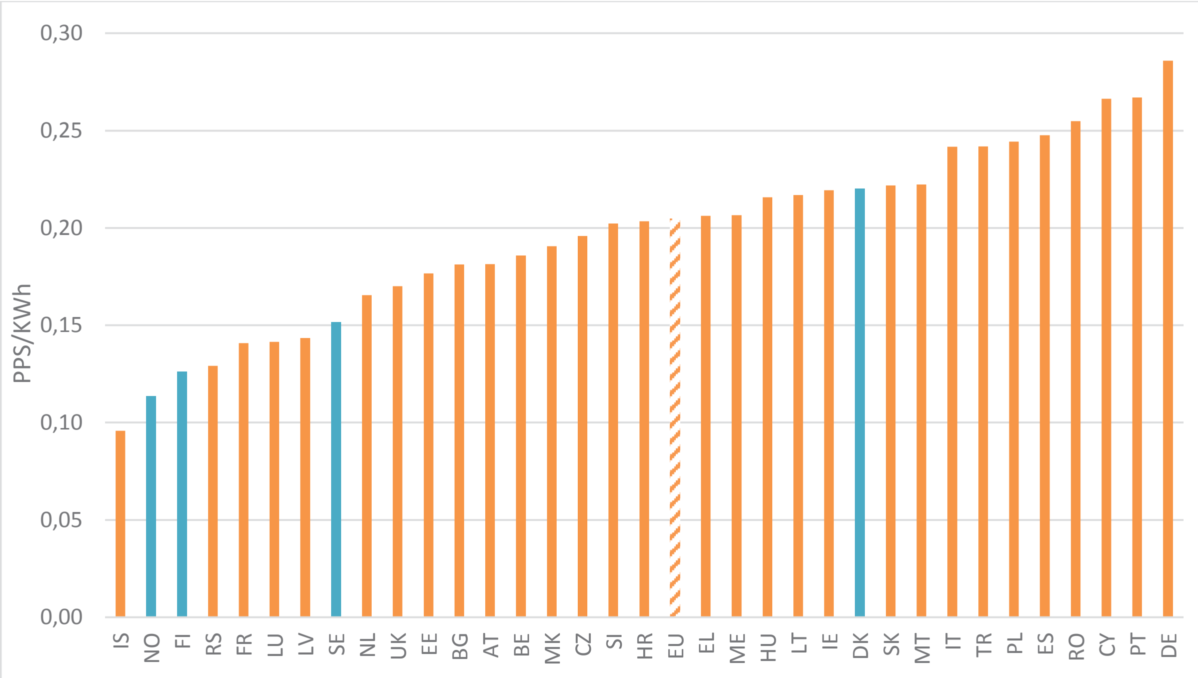

Figure 5 – Electricity prices for household customers in the European countries during 2014 (PPS/kWh)
Data source: Eurostat

Clearly, Norway, Finland and Sweden are among the European countries with the lowest relative electricity prices when the price level differences are taken away. This fact may question customers' incentive to change supplier of only price considerations. When choosing to change suppliers end-users may be responding to other stimuli – e.g., innovative retail offers that combine electricity delivery with other services (Goett et al. 2000). The delivery of new types of electricity retail services will be enabled by the set of smart grid technologies within the future power system (as suggested by Samadi et al. (2012) and Shengrong et al. (2011)).

3.2.1 Electricity retail offers in a smart grid environment

At present, most electricity end-users in the Nordic countries are being charged according to an average price profile for their monthly consumption. Consumers are thus not exposed to the hourly variances in prices that are to be found at the wholesale market and their ability to respond to price signals is minimal. Even if consumers choose to adjust their electricity consumption profile on a diurnal or weekly basis, the effect on final expenditures will be limited due to the use of averaged pricing. Thus, the retail prices faced by end-users are unable to reflect stringent situations in the power system, which are otherwise reflected in the wholesale prices. As noted by Mirza and Bergland (2012), the limited price response exhibited by electricity consumers represents an inefficient market outcome for several reasons: consumers tend to "over-consume" in periods with high prices, and "under-consume" when prices are low; producers may exercise market power, thus increasing price volatility and contributing for wealth transfers from end-users to suppliers.

The existence of a competitive retail market and a variety of pricing contracts helps to mitigate the risk of price spikes for the end users. In particular, for the Norwegian retail market, the most broadly used contracts are:

- *Spot price contracts* for which a fixed price markup is added to the wholesale market spot price, to pay for retailers' services.
- *Fixed price contracts* that have the electricity price fixed over a period of time (normally 1, 3 or 5 years), thus hedging against the risk of price changes.
- *Variable price contracts* which have fixed price but retailers can change it on a weekly basis. Yet, the customers should be informed about the price change.

In addition, modifications of the above tariffs can be found in the retailers' portfolio of offers – such as a spot tariff with a price ceiling. Consumers' preferences for which type of retail contract to choose have been changing with the years (Figure 6). As shown in Figure 6, during 2012-2014 the spot price contracts have had the largest share, followed by the variable price contracts. In the third quarter of 2014 the share of spot price contracts slightly decreases on behalf of an increase in the variable and fixed price contracts - a fact to prove that customers are observant of electricity retail offers and have readiness to switch. Also, the share of fixed price contracts has been low and slightly decreasing throughout the period, indicating that consumers consider price contracts that are at least partially connected to the wholesale market as more preferable. In this respect, a tighter connection to the wholesale market, in the form of RTP retail contracts should not be regarded as either undesired or unacceptable for the consumers.

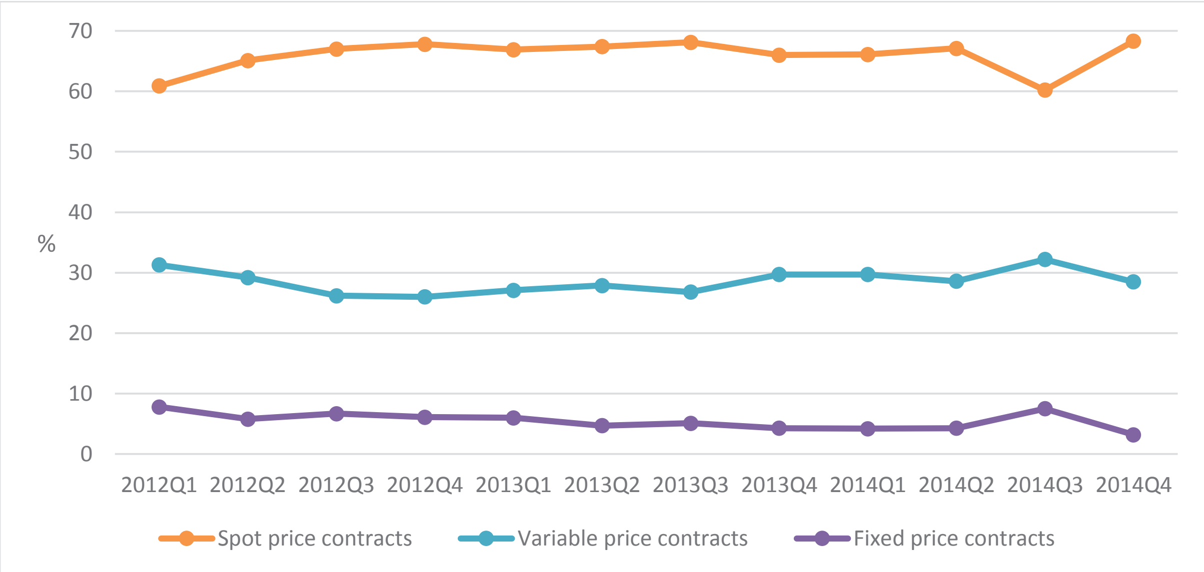

Figure 6 – Percentage share of retail contracts in the Norwegian end-user market. Quarterly data for 2012-2014.
Data Source: Statistics Norway

Despite the existence of a variety in the contract offers, there is a considerable potential for improvement in the end-user market's efficiency. As Mirza and Bergland (2012) acknowledge, an efficient retail market is one in which retailers directly pass on the price changes from the wholesale market to the end-users. Not surprisingly, the possibility to pass on the wholesale market price with the help of RTP has provoked wide research interest.

Smart meters and communication technologies, as elements of the future smart grid, will allow for communicating price signals to the end users in real time. The capability of RTP tariffs to both increase price elasticity and reduce overall consumption has been discussed by Allcott (2011). Furthermore, of particular importance, also with respect to the supplier-centric model described in Section 3.2, is the possibility of retail offers, such as RTP or dynamic pricing, to accommodate demand flexibility in the system, so that easier integration of VRE is ensured. The topic is discussed, among others, by Savolainen and Svento (2012) and Finn and Fitzpatrick (2014a). Also, as shown by Yang et al. (2014), demand response achieved through RTP is capable of balancing supply and demand, which is specifically important for a system with increasing shares of RES in the generation mix. Set in the context of a smart grid dominated power system, RTP can further contribute for the optimal accommodation of electrical vehicles (EV) (Anderson 2014), utilizing the management of heat pumps (Schibuola et al. 2015) and thermal loads (Agüero-Rubio et al. 2014), as well as to optimize the use of grid-connected storage (Dufo-López 2015). Considering the vast potential of RTP, it is included in this thesis as a future smart grid enabled demand response measure that can assist system balancing and utilize consumption when more power generated from RES is being fed into the grid. In this regard, Paper IV elaborates on the market effects of increased within-day price based demand response, e.g., facilitated through a RTP pricing tariff, and discusses on how demand response can improve the integration of VRE on a large scale.

But retailers' opportunities within a smart grid environment can be many more. New technologies and smart meters to allow for two-way communication will open up for new possibilities within the consumer-retailer relationship (European Technology Platform SmartGrids 2010). As stated by the European Technology Platform, the retailers' role could be defined as a "resource for smart grid development." Utilizing energy efficiency and maximizing profits retailers may extend their offers to include specific customer-oriented retail products that can also take in use the functionalities offered by the smart grid. Such retail services may be related, for example, to new pricing methods (e.g. RTP or dynamic pricing), EV, micro-generation at customers' premises, electricity storage, or to modifying the existing pricing contracts and bundling these with other services. The wide range of new opportunities may impact the retailers' market strategies. Assuming a retail market setting in which the wholesale electricity price will be passed on to the end users with a fixed markup added to it, it is of interest to see what effect this wider choice of opportunities may have on the retailers. Specifically, what will be their price and service decisions and how their profits may change? These are the research questions that Papers II and III aim to answer on.

4. Data and methods

The models applied in the research articles include four different approaches: econometrics, optimization with the help of nonlinear programing, complementarity and a linear partial equilibrium approach. The program Stata has been used to conduct the econometric analysis, while the optimization problems have been solved with the help of the GAMS software.

4.1 Data used in the models

The data used in the separate articles varies in size and age. For the econometric analysis in Paper I are used time-series for a six-month period in 2012. The data for the three main groups of variables - regulating prices, spot prices and volumes of regulating bids are taken from the Nord Pool Spot database.

The data used in the second and third papers have several sources: the coefficients used in the optimization model in Paper II are mostly based on assumptions that are related to the referenced literature. In addition, data for 2012 from the Norwegian Water Resources and Energy Directorate (NVE), received as a result of a private enquiry made to the Directorate, have been used to quantify the electricity retailers' market base. For the simulations in Paper III are used most of the data collected for Paper II. However, a different approach is applied when quantifying electricity retailers' service level. While in Paper II the service level is equalized to an investment in service value in money terms, in Paper III service level originates from collected in 2014 data on the various retail offers, where each retail offer assigns certain weight to the retailer's service level. It is important to note that in both papers service level is actually represented by a proxy for service.

In the fourth paper a comprehensive equilibrium model that uses a larger amount of data is applied. The model includes seven countries in Northern Europe and is calibrated with real data which dates back to 2012-2013 and has the databases of NordPool, Entso-E, Statnett, Tennet, EEX, the UK Statistics Authority and the EC as its origin. Installed generation capacity, electricity demand, production from RES, hydro inflow, transmission capacities, export balance, and fuel and CO2 prices represent the exogenous parameters in the model and the main amount of data.

4.2 Methods applied

Each of the papers included in this thesis applies a different modeling tool. But while Papers I and IV use completely different types of models (an econometric model and a linear partial equilibrium model), the models of Paper II and Paper III are related. The nonlinear optimization model from Paper II is transformed into a mixed complementarity problem in Paper III. The combination of different modeling tools in this thesis is considered necessary for making realistic projections of the impact that the variety of changes in the future power system may have.

4.2.1 Econometric analysis

In the econometric analysis in Paper I the balancing market prices for up- and down-regulation are presented as dependent on the spot prices and the volumes of regulating bids. The functional form used in the model resembles the one used by Skytte (1999). However, Skytte (1999) investigates the impacts of the total amount balancing power activated, while in Paper I the focus is on the increasing volumes of bids as a result of the NBS model and integration in the settlement procedures. The data used for the regression has hourly resolution and includes the bidding areas[8] in Norway, Sweden and Finland – i.e., a total of ten areas. The constant terms, the coefficient of determination R^2, and the coefficients on the regression equation's independent variables are estimated using Stata software.

The nature of the data used in the model has made it possible to estimate the elasticity coefficients as per bidding area and to relate those to the bidding areas' transmission capacity characteristics and generation mix. Furthermore, the regulating price elasticities attained in Paper I are later used in Paper IV to make projections about the effect of DR on the balancing costs.

4.2.2 Nonlinear programming

The nonlinear program applied in Paper II maximizes the profit of electricity retailers (net of service investment costs) where the profit is constrained to vary only within certain limits. Within a two-retailer model the profit of each retailer depends on the decisions for own price markup and service

[8] Due to constraints in the transmission capacity the Nordic power exchange Nord Pool has been divided into the following bidding areas: 2 in Denmark (DK1, DK2); 5 in Norway (NO1, NO2, NO3, NO4, NO5); 4 in Sweden (SE1, SE2, SE3, SE4). Finland still represents only one bidding area (FI). Among the Nordic countries only Finland, Norway and Sweden are to participate in the NBS model.

level, but also on the competitor's price markup and service, and on the demand they have to satisfy. A constraint on the variance of the expected profit is used to limit the risk for retailers. The price and service dependences are defined through elasticity coefficients, assumptions for which are made with the help of relevant literature sources (Halvorsen & Larsen 2001). The demand faced by the electricity retailers is modeled as an expected value for the market base that is calculated using NVE's data on number of customers per electricity retailers and the average yearly amount of electricity consumed per household.

In the simplified two-retailer model (with retailer 1 and retailer 2) only the decisions taken by one retailer are considered, while the price markup and service values for the other are held fixed. In several consequent simulations the price markup and service decisions of retailer 2 are being changed and the impact on retailer 1 is then analyzed. The simulations include the following five changes in the basic model assumptions:

1. The price markup for retailer 2 decreases
2. The price markup for retailer 2 increases
3. The service level for retailer 2 increases
4. Both the price mark-up and service level for retailer 2 increase
5. The risk constraint on profit is relaxed

After ensuring that the requirements for sufficiency of the Karush-Kuhn-Tucker conditions are met, the optimization problem is solved using GAMS software and BARON solver. The model's results are used to describe how a retailer's decisions on price markup and service level may change when retail competition is intensified and under different levels of risk aversion.

4.2.3 Mixed complementarity

In Paper III the nonlinear program from Paper II is transformed into a mixed complementarity problem through which the optimality conditions of rival retail firms are solved together. The mixed complementarity model applied has several features that further distinguish it from the model in Paper II: it introduces a new approach to quantifying service with the help of a system of weight points that jointly compose the service level proxy; it defines the relationship between price markup and service level by using econometric estimation; it can be extended to a larger number of competitors; it allows identification of an equilibrium among suppliers.

Within the complementarity problem the price markup-service relationship resembles the functional form of an (inverse) market demand function defined by Gabriel (2011). Using real data on the retail offers of suppliers in the Norwegian retail market, their service levels are quantified by proxy that is built on a system of weight points. Among all Norwegian suppliers data is collected only for the ones with spot price tariffs in their product portfolio. Further, econometric estimation is used to find the relationship between the suppliers' price markup and service. The price markup-service relationship is integrated within the optimization problem for each retailer, so that each retailer's decision on what price markup to charge will depend on not only own but also other retailers' choice for service level.

To make it easier to analyze the trends in changes in the equilibrium price markups and profits, the model applies a simplified version with only two retailers. However, a model configuration for the case of n competing retailers is provided. In addition, the decisions of each retailer have been constrained by an upper cap on the service level proxy, to signify the difficulty retailers have to innovate their service offers on a short term basis.

The above described model setting is used to run several simulations (besides a Base Case model simulation) for which the retailers' equilibrium price markups and profits are investigated under the following changes:

1. Change in the upper cap on the service level proxy – to reflect a retailer's increased capability to innovate in the short run
2. Retailers with different market base compete in the market (in the Base Case simulation the average market base value is used)
3. The willingness of end-users to actively choose retail products and services increases as a consequence of increased knowledge on retail offers and smart grid functionalities
4. Demand flexibility becomes integrated in the retailers' portfolio of offers

The MCP in Paper III, as well as the nonlinear program in Paper II, involve a number of assumptions, most importantly related to quantifying the service level proxy, the elasticity coefficients and the retailers' market base. Yet, it would have been hardly possible to analyze the future trends in retail price markup, service level and profit, unless these key assumptions were made.

4.2.4 Balmorel

In Paper IV the linear partial equilibrium model Balmorel, that simulates production, transmission and consumption of electricity, is applied. In the model the electricity consumers' utility function minus the cost of generation, transmission and distribution is maximized. As a result, the generation per technology, time unit and region is calculated. Balmorel assumes perfect competition – i.e., there is no market power and all actors operate in an economically rational way in order to maximize profits (Hedegaard 2013). The optimization problem includes a number of constraints to ensure that the energy flows are in balance, the available transmission capacity is not exceeded, and that power is produced within the maximum capacity level of the generation units. The model has a fine resolution in time and space. The yearly time frame for which the optimization takes place is divided in seasons, and further in weeks and hours. The main geographical entities – the countries – are divided into regions that are connected by transmission lines, and the regions are divided into areas.

Balmorel provides free access to its code (programmed in GAMS) which allows for model calibration and independent model developments. In this regard it has been possible to develop a Balmorel model version for which demand response is endogenously modeled within a power system with diversity in the generation mix. The model differentiates between geographical units, thus representing transmission possibilities and costs on a national level. This feature has helped to investigate the specific market impacts of demand response per country and in relation to the generation mix. In addition, the model uses time resolution within the year which helps to represent demand variations and intertemporal storage (Ravn 2001). Model simulations can be run with fine temporal and spatial resolution for both short term and long term optimization horizons.

The specific version of the Balmorel model developed in Paper IV has its major methodological strength in modeling both thermal and hydropower dominated systems. The model has a relatively detailed representation of the Norwegian and Swedish hydrological systems, with 15 regions in Norway and 4 in Sweden. One run-of-river plant and one reservoir hydro plant are modelled in each region. Inflow series is based on historical data obtained from Statnett. The specificity of the thermal plants' marginal costs is modeled through a division into sub-technologies and through limits on thermal flexibility that are represented by ramping conditions. The production profiles of the VRE sources are exogenously given and these vary on an hourly level in correspondence to historical observations for wind, PV and run-of-river generation. Finally, demand flexibility is modeled endogenously. For the purpose an assumption that within the day a certain share of the observed difference between the daily maximum and the average demand may be shifted from one hour to another is made.

Methodological approaches of a similar form have been used in other studies and for various purposes. Modeling the electricity generation system until 2020 with the help of the TIMES model, Pina et al. (2012) show that DSM can delay the investments in new VRE generation facilities and improve the operation of the existing ones. Karlsson and Meibom (2008) use Balmorel to investigate a possible long term investment path (until 2050) for the Nordic energy system where the penetration of RES and hydrogen in the transport sector is high. Juul and Meibom (2012) add a transport model extension to the Balmorel model structure to analyze the optimal configuration and operation of the power and road transport systems in Northern Europe in 2030. Hedegaard (2013) uses both the EnergyPLAN and the Balmorel model to investigate how heat pumps, flexibility measures in district heating and EV can improve the integration of wind power generation towards 2030. Due to the changing nature of the power system (as described in Chapter 1), policy makers need insight into the future developments that will assist them in taking decisions and designing the regulatory framework. To have detailed – in time and space - power system modeling tools, such as the Balmorel model, may thus become increasingly important.

At present, the Balmorel model is being developed and distributed as an open source and is predominantly used by Danish research and educational institutions (Technical University of Denmark, Danish Energy Assosiation, Ea Energy Analyses). Being able to model in detail the Norwegian and Swedish hydropower systems, and to represent thermal power generation realistically, the Balmorel version used in this thesis represents a substantial improvement to its previous versions. The improved version can be used and further expanded to model future developments in the power system in a credible way.

5. Results

In this chapter the main results from Papers I-IV are presented and consequently connected in the context of this thesis' goals.

5.1 Changes in the regulating price

The econometric estimation in Paper I quantifies the impacts of the volumes of regulating bids and the electricity spot prices on the balancing prices. The results from the regression model indicate that the price for up-regulation slightly decreases as the volumes of up-regulating bids get higher. The values of this decrease are in the interval between 0.02% and 0.14% for the various price areas of Norway, Sweden and Finland included in the model (given the volume of up-regulating bids is increased by 1%). When it comes to the down-regulating prices, a 1% increase in the volumes of down-regulating bids will result in a minimum of 0.06% and a maximum of 0.26% increase in the prices for down-regulation for the different price areas. Table 4 presents the price areas the balancing prices of which are to be most and least influenced by a change in the regulating bids' volume.

Table 4 – Impact of increase in the volumes of regulating bids on the balancing prices.

Impact on the balancing prices		Price area and % change	
		Given 1% increase in the volume of bids for:	
		Up-regulation	Down-regulation
↓	Most impacted	FI (-0.14)	NO5 (0.26)
	Second most impacted	NO4 (-0.06)	NO2 (0.25)
	Third most impacted	SE1 (-0.05)	NO3 (0.23)
	No statistical significance found	NO5	SE1 and FI

Based on the estimated relationships for historical data we discuss the impact that possible changes in the volumes of regulating bids will have on the balancing prices with the forthcoming market changes. As the model results indicate, the down-regulating prices are more sensitive to an increase in the volume of bids as compared to the up-regulating ones. The results on sensitivity of the balancing prices with respect to the spot price are somewhat more ambiguous in nature. Yet, on average, the up-regulating prices are found to be more sensitive to an increase in the spot prices than the down-regulating ones.

According to the estimation results in Paper I the price areas most sensitive to changes in the regulating bids' volumes are not the ones for which the greatest bid volumes are being traded. Therefore, a suggestion is made that other factors, such as transmission capacity or long-term contracts for delivery of balancing power, might be determining the level of impact. In addition, the results from the econometric estimation are analyzed with respect to the generation mix and seasonal variation (winter versus summer) in each price area in the model. The sensitivity of the down-regulating price with respect to the bids' volume is higher for the Norwegian hydropower dominated price areas, and during winter time. On the contrary, the up-regulating prices are most sensitive to changes in the bids' volume for Finland where the amount of hydropower in the generation mix is lowest.

When comparing the summer and winter seasons, the coefficient estimates on the spot prices indicate that the down-regulating price is more sensitive to a spot price increase during the summer months. This could be explained with the balancing parties' preferences to trade their free capacity[9] in the spot market, rather than reduce production in order to give a down-regulating bid on the balancing market. Finally, the results indicate that in some cases an increase in the volume of down-regulating bids could actually decrease the down-regulating prices (e.g., during summer periods and for price areas where large amounts of down-regulation is needed).

5.2 Retailers' price and service decisions

For the analysis in Paper II are run 5 model simulations. The applied model is simplified to only 2 competing retailers. The simulations aim to find the optimal price markup and service values for retailer 1, given predefined price markups and service values for retailer 2. The following characteristics are common for all five simulations: (i) 20 iterations in each simulation; (ii) retailer 2's price markup and service level are predefined; (iii) the impact on retailer 1's price markup, service level

[9] In general, power producers have more free capacity available during summer months when consumption is typically lower.

and profit is investigated. The model results have hourly resolution and the profit values represent the expected hourly profit from price markup. The differences in the model simulations are summarized in Table 5.

Table 5 – Model simulations in Paper II

Simulation	Change in predefined values (per iteration)
1	Retailer 2's price markup decreases by 5%
2	Retailer 2's price markup increases by 5%
3	Retailer 2's service level increases by 0.5*
4	Retailer 2's price markup increases by 5% and its service level by 0.5
5	The variance of the expected profit from price markup increases by 10%

* In Paper II service level of 0.5 corresponds to a value of 500 NOK/h investment in service.

The key results from the model simulations are as follows:

Simulation 1: When the price markup of retailer 2 is being constantly decreased, retailer 1 will have a steadily decreasing profit (Figure 7). Retailer 1 keeps its price markup lower than its rival until the last iteration where retailer 1's markup is 1.44 øre/kWh, compared to 1.43 øre/kWh for retailer 2. The overall price markup level for the last iterations is so low that consumers will not feel the need to switch supplier and retailer 1 is not motivated to continue offering a lower price markup. The service level of retailer 1 remains constant at 5.83 (investment in service value of 5830 NOK/h) but starts decreasing from the 14th iteration. The 20 iterations give results numbered 1 to 20 on Figures 7-11, while results defined by B represent the starting (Baseline) values.

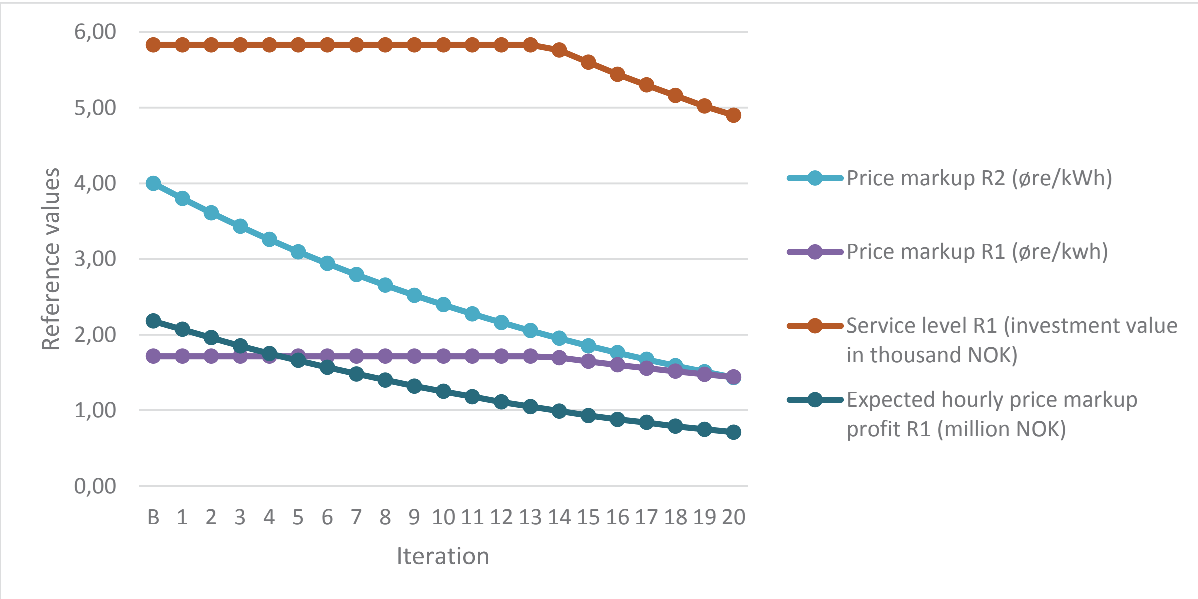

Figure 7 – Impact of decreasing the price markup for retailer 2 on retailer 1' price markup, service level and hourly profit

Simulation 2: When the price markup of retailer 2 increases, retailer 1 may get higher profits (Figure 8). Retailer 1 responds to retailer 2's price markup increase by offering lower price markup at higher markup levels and higher markup at the lower markup levels where customers are less sensitive to the difference. Retailer 1's price markup and service increase until the 15th iteration from where on they stay constant. A reason for that may be retailer 1's level of risk aversion – a further increase in the price mark could drive back its customers, despite the higher service level.

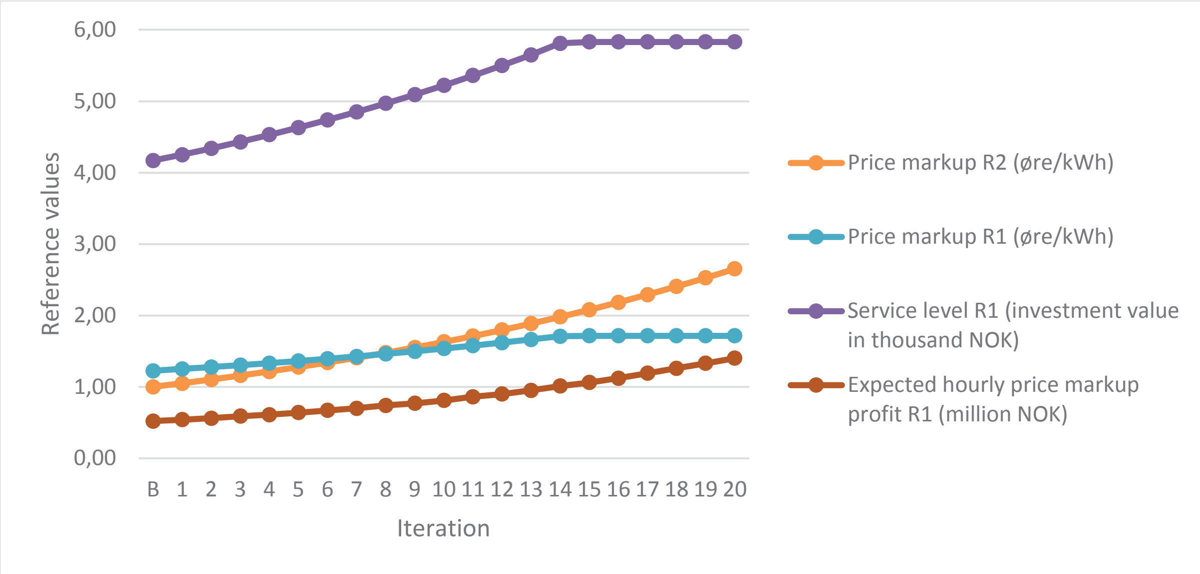

Figure 8 – Impact of increasing the price markup for retailer 2 on retailer 1' price markup, service level and hourly profit

Simulation 3: When retailer 2 increases its service level the expected profit of retailer 1 decreases (Figure 9). The price markup and service level of retailer 1 stay constant for the first iterations but start dropping after the service level of retailer 2 is increased above 4.5.

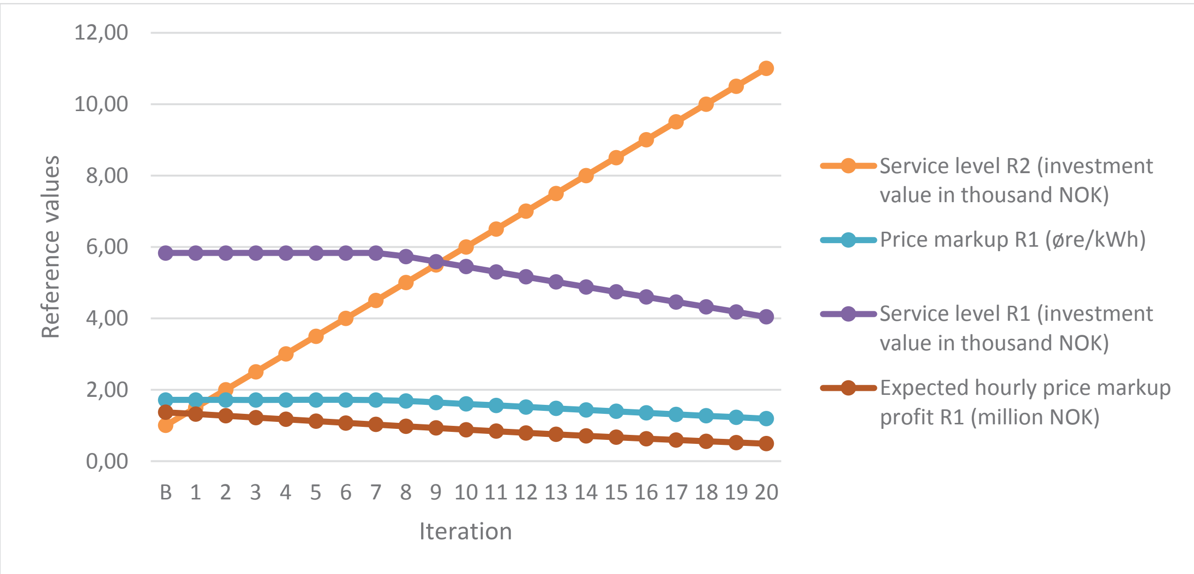

Figure 9 – Impact of increase in the service level for retailer 2 on retailer 1' price markup, service level and hourly profit

Simulation 4: The simultaneous increase in retailer 2's price and service level may have a two-sided impact on retailer 1. Retailer 1 is to initially decrease its price markup, service level and profit, which then increase after the 12th iteration (Figure 10).

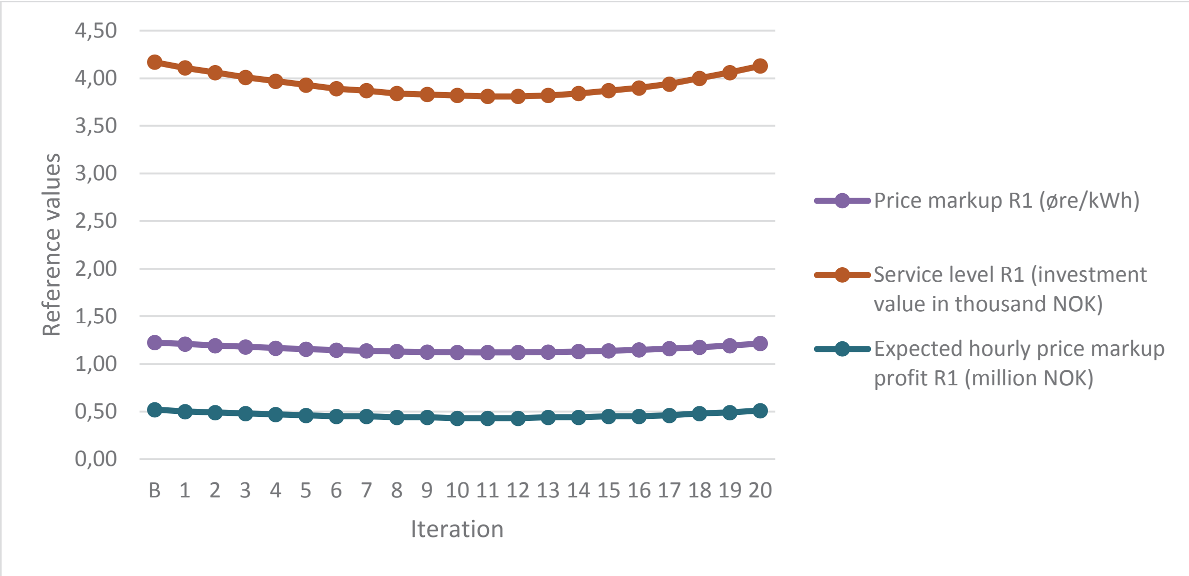

Figure 10 – Impact of increasing both the price markup and service level for retailer 2 on retailer 1's price markup, service level and hourly profit. Price markup and service level for retailer 2 are increasing as in simulations 2 and 3

<u>Simulation 5:</u> In the case where the variance of the expected profit, used as a constraint in the model, is allowed to increase, the expected profit of retailer 1 increases (Figure 11). The increase is diminishing as the percentage increase in the expected hourly profit declines although the percentage increase in the maximum allowed variance is kept constant. And the price markup and service values increase as well.

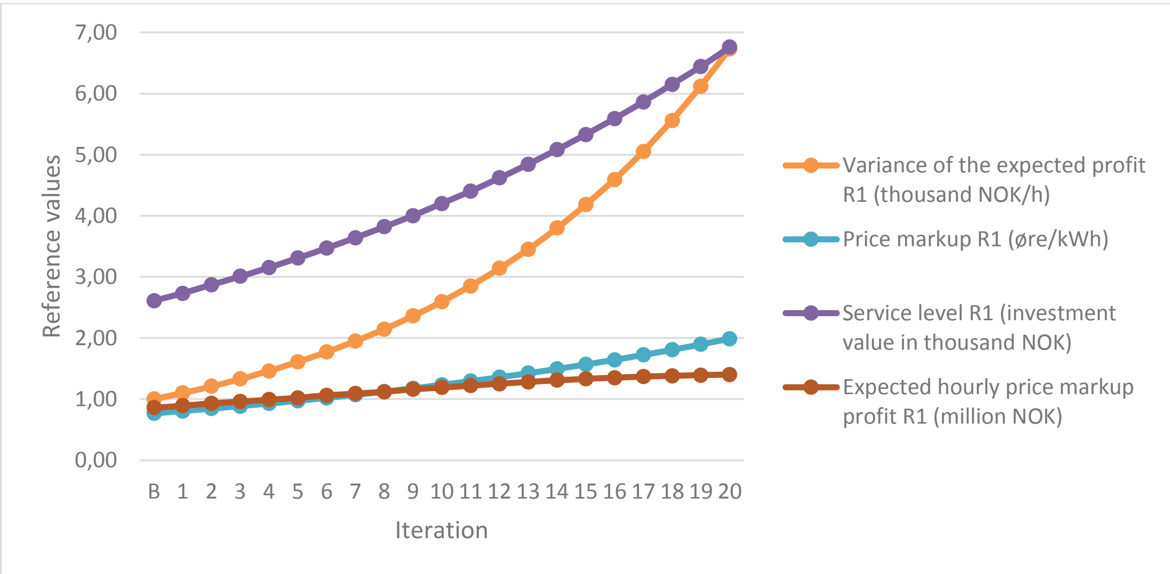

Figure 11 – Impact of increasing the variance of the expected profit for retailer 1 on retailer 1's price markup, service level and hourly profit.

5.3. Equilibrium retail price mark-up and profit

Paper III applies a MCP that gives the equilibrium price markup and profit under different assumptions made for the retailers' market environment. In particular, the parameters defining the retailers' capacity to enrich their service offers, their market base, demand sensitivities and "price markup versus service" preferences are varied in the model. Model simulations are run for a simplified case with only two competing retailers.

Under a Base Case scenario, for which the set of retail service offers has an optimal level, the equilibrium price markup is 4.06 øre/KWh and the yearly profit from price markup is 16.4 million NOK. In the Base Case the two competing retailers are of an average size. The equilibrium price markup and profit for both lower and higher service levels are presented in Table 6.

Table 6 – Equilibrium price markup (øre/KWh) and yearly profit (million NOK) as retailers' ability to innovate increases. The values for the Base Case are marked in grey.

Retailers' ability to innovate in service increases →																				
Markup	2.2	2.4	2.5	2.7	2.8	2.9	3.1	3.2	3.4	3.5	3.6	3.8	3.9	**4.1**	4.2	4.3	4.5	4.6	4.8	4.9
Profit	9.1	9.6	10.2	10.8	11.3	11.9	12.5	13.0	13.6	14.2	14.7	15.3	15.9	**16.4**	17.0	17.6	18.1	18.7	19.3	19.8

The change in profit as retailers of different size compete is presented in Figure 12 below. The model is run for 20 consequent iterations. The small retailer's demand base increases by 20%, while the larger retailer's market base decreases by the same percentage at every step (1 to 20).

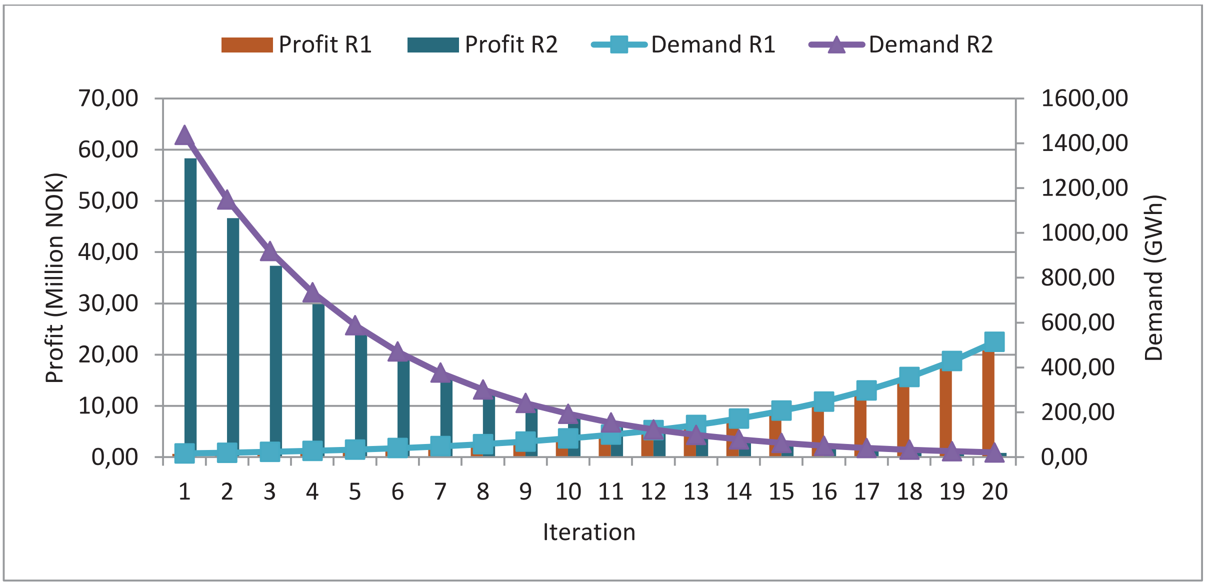

Figure 12 – Retailers' yearly price markup profit when demand changes: small (R1) versus large (R2) company

In a case where the small retail company has a higher possibility to innovate in service (HS), while the possibility for the larger one is limited (LS), both retailers' profits shrink in size for all demand levels as the equilibrium price markup is reduced from 4.06 to 3.2 øre/KWh. This is illustrated in Figure 13 where for each iteration step the demand base for retailer 1 increases and that of retailer 2 decreases.

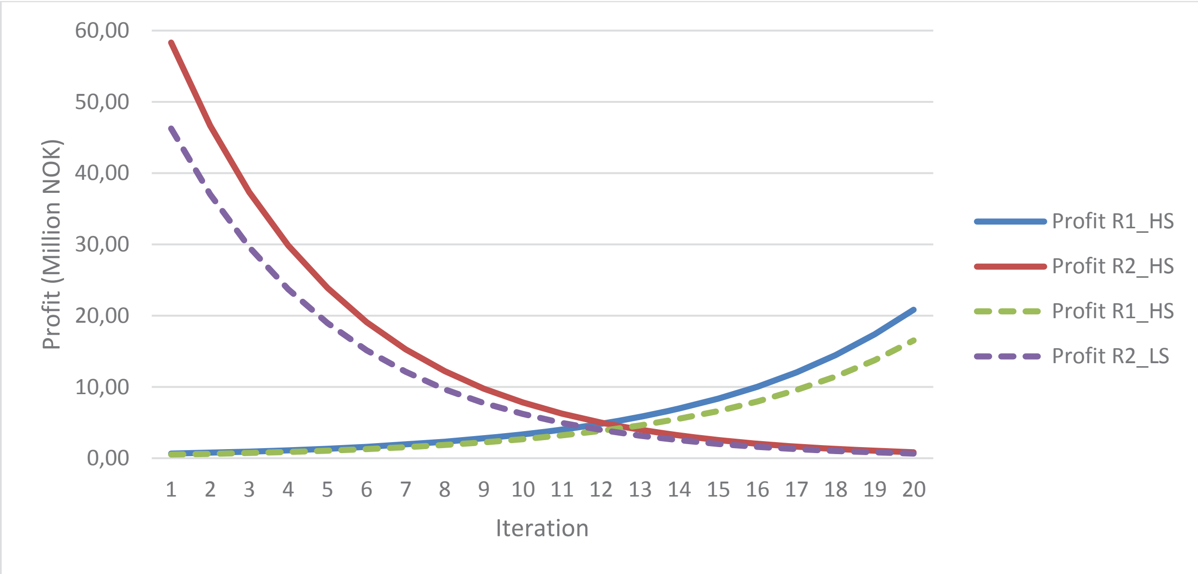

Figure 13 – Changes in the yearly profit for two retailers of different size when the ability of retailer 2 to innovate in service is decreased (from HS to LS). Dashed lines present the reduced profit.

Further on, Paper III provides results for the equilibrium markup and profit when the parameter defining the relationship between a retailers' own markup and the combination of the own and the rival firm's service level is varied (Table 7). In Paper III the parameter is defined as the slope in the "price markup versus service" curve and is noted by "theta".

Table 7 - Equilibrium price markup and profit as the slope of the "price markup versus service" curve ("Theta") increases

Theta increases →																				
Markup	2.5	2.7	2.9	3.1	3.3	3.6	3.8	4.1	4.5	4.8	5.2	5.7	6.2	6.7	7.3	7.9	8.6	9.4	10.3	2.5
Profit	10.3	11.0	11.7	12.5	13.5	14.5	15.6	16.8	18.1	19.6	21.2	23.0	24.9	27.1	29.5	32.1	34.9	38.1	41.6	10.3

The consequent analysis carried in Paper III shows how a retailer's demand base, ability to innovate in service and the price markup-service ratio jointly impact the change in profit. In this regard it could be expected that as theta increases innovative retailers may experience a moderate increase in profits, after an optimal combination of theta and service level is met.

Finally, the results in Paper III reflect the impact of changes in the own-price and cross-price sensitivity, associated with increased demand flexibility. A 10% increase in the sensitivity parameters reduces the equilibrium markup and yearly profit to 2.38 øre/kWh and 9.64 million NOK respectively (as compared to the Base Cases's 4.06 øre/kWh and 16.44 million NOK).

5.4. Market impacts of DR

Paper IV investigates the market and system impacts of DR in a future Northern European energy market with large share of VRE. In this regard the study analyzes the following trends:

- Changes in production mix and consumption profiles when DR is introduced
- Influence of DR on the cost of electricity in terms of changes in electricity prices, consumers' cost and system costs

- Changes in profit for the different power technologies when introducing DR
- The possible role of DR for integration of VRE
- The dependency of DR impacts on the specific future power market developments

Four scenarios with different amounts of potential DR to be utilized in the future power system are analyzed in the model: a Baseline scenario where the today's level of DR is assumed, and scenarios with Moderate, Full and High response for which the potential for DR increases in the indicated order.

Under the assumption for a future Northern European power system with an almost 50% share of RES, the model simulations show that increase in DR reduces production from mid-merit technologies (reservoir and pumped hydropower and natural gas), while production from coal and lignite, which function as base load power, is increased. When DR is increased power production from natural gas and coal during off-peak periods increases as well. This causes an increase in the total coal power generation, despite the reduction during peak hours and the total GHG emission increase by 0.6 Mton in the Full flexibility scenario (given the model's assumptions for future fuel and carbon prices, consumption growth and capacity mix). The mid-merit technologies experience reduced daytime and increased nighttime generation while the annual power generation from VRE is increased.

The consumption profiles for Norway (a country dominated by hydropower generation) and Germany (a country with high amounts of wind and solar power in the generation mix) are compared. For Norway, in both summer and winter seasons, a shift in the hourly demand from peak demand daytime hours to low demand nighttime hours is observed. For Germany the impact varies with the seasons – the pattern is similar to Norway during winter time, but during summer time consumption in high demand hours increases, as DR helps accommodating the increased supply of solar power.

The power price impact of increased DR varies among countries, seasons and time of day. The average intra-day price variation (the standard deviation of the price within a day) is reduced by 12-22% for all countries. The average daily maximum price decreases by 3-4% in the thermal power based countries while the decrease for the countries with high share of regulated hydropower is more than two times lower. In general, DR is found to have minor influence on the average electricity price and therefore the reductions in the consumers' cost of electricity are moderate – less than 1% cost reductions in most cases.

The profit for the producers of VRE increases for all types and locations of VRE generation as DR increases. The total annual profit from wind power generation increases with 51 million euro, and that from solar and run-of-river hydropower with respectively 10 and 19 million euro in the Full flexibility scenario (as compared to the Baseline). The profit for thermal power and reservoir hydropower producers is reduced. In particular, for coal and lignite, profit is decreased despite the increase in total production due to lower peak prices and moving production to nighttime hours.

Paper IV shows that DR can help for the integration of VRE in the following ways: DR reduces the need for peak power generation and the short term price variations, thus decreasing the need for balancing reserves and for ensuring capacity adequacy; DR can provide system benefits reducing the annual and daily maximum residual demand level (total demand minus production from VRE) and therefore helps overcome the technical and economic challenges related to integration of VRE.

Sensitivity analysis, in which several basic model parameters are being varied (levels of power consumption, VRE generation, nuclear power generation, and fuel and carbon prices), indicates that the model's results are generally robust to the underlying assumptions on future developments in the power market.

5.5. The joint effect of market changes in the future power system

The papers presented in this thesis have different focus and apply different methods. The overall scope of the PhD work is wide and includes the Nordic balancing and end user markets, as well as a future Northern European power system with high share of VRE in the generation mix. Despite the fact that the papers' results concern different market changes, they are related in the means of their joint contribution to building a realistic outlook for the future power market impacts. And even though the coming market changes are specifically concerning certain parts of the power sector, their impact can be felt by most actors in the power system.

In the core of the four studies building up the thesis lie three major power system changes: increased amount of VRE in the generation mix, market integration and smart grid. With the help of different modeling tools the PhD work investigates how these changes will impact the balancing prices for up- and down-regulation, the price and service strategy of electricity retailers and their equilibrium price markup and profit, the power generation mix, consumption profiles, system costs, power prices and consumers' costs, and producers' profit.

Although the four papers focus on different topics, they are semantically related. Paper I analyzes the changes in the regulating prices associated with an NBS model. The NBS model is to contribute for the creation of a common Nordic retail market, the impact of which is investigated in Papers II and III. Increased competition on the retail side, as a consequence of the common Nordic end-user market, can be expected to stimulate retailers to offer new (or improved) services. In a future smart grid dominated power system the electric power suppliers will most probably utilize the smart grid functionalities in their portfolio of retail offers. In this respect electricity retail contracts to allow for exercising DR on the consumers' side may become an important part of the retailers' business. Furthermore, as showed in Paper IV, DR measures may be of great help for improving the integration of VRE and thus reducing the need for balancing reserves, and balancing power is the topic discussed in Paper I. Figure 14 illustrates the key issues discussed in the research papers and their connection.

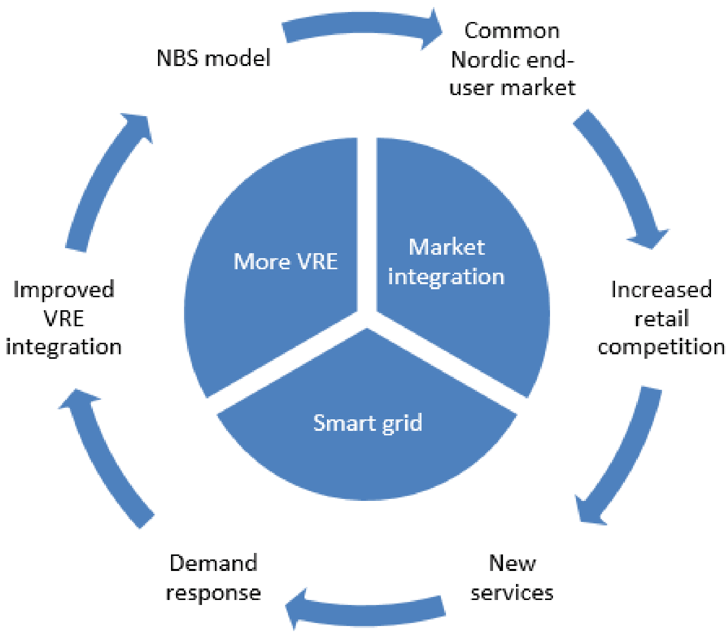

Figure 14 – Key issues discussed in Papers I-IV and their connection. The three major market changes lying in the core of the research articles are presented in the center.

6. Discussion and conclusions

This chapter discusses the PhD work's contribution in the sense of answering the main research question and fulfilling the thesis' goals. As part of the discussion on the fulfillment of goals, the thesis' results and analysis are compared to that of other studies. Finally, key assumptions, methodological limitations and possibilities for further research are presented.

6.1 Answer to research question

The research question to which the thesis provides a scientific contribution is:

- *In the presence of a smart grid environment - what could be the economic effects of market integration and increased demand flexibility on the balancing and end-user markets, and on a power system with high VRE shares in the energy mix?*

To answer this research question the PhD study applies different methods through which the economic effects in different parts of the power system are analyzed: the Nordic power balancing market; the Nordic electricity end-user market; the Northern European power production, consumption and market sectors. The models' results are analyzed in relation to their specific time and space attributes whenever applicable.

The economic effects investigated in connection to the balancing market represent changes in the balancing market price as a result of an increase in the volume of regulating bids. An increase in the volume of bids may be a consequence of establishing an NBS model in the Nordic region. The changes in the balancing prices are analyzed with the help of an econometric model that uses historical market data. In the model the prices for up- and down-regulation are presented as dependent on the spot prices and the volume of up- and down-regulating bids. The model's results indicate that the down-regulating price is more sensitive to the regulating volumes than the up-regulating price and show relatively large differences in the sensitivity to spot prices and bid volumes across different areas and seasons.

The economic effects in the Nordic end-user market have been investigated in relation to the establishment of a common Nordic retail market in which retail competition is expected to intensify. The process of retail market integration is seen in the shadow of smart grid penetration that will facilitate innovation in the retailers' service offers. With the help of a nonlinear program the effects on competing retailers' profit, price markup and investment in service are analyzed. The program is run for a two-retailer case and in the course of several simulations it has been shown that price and service decisions made by one retailer have a strong impact on the market strategy of the other and that the size of this impact depends on the overall price markup level. Further on, the nonlinear program is transformed to a MCP that quantifies the equilibrium price markup and profit and shows how these depend on the retailers' market base and ability to innovate, and on customers' knowledge.

Within a Northern European power market perspective the investigated economic effects are related to an increase in the electricity DR. By applying a detailed partial equilibrium model it has been shown how increased within-day DR will impact the power generation mix, the average prices and consumers' costs and the producers' profit, and how DR may contribute for improving the integration of VRE. The results indicate that increased demand response will have low impact on the average power prices and on consumers' cost of electricity and that it will reduce considerably the annual and daily maximum residual demand, the short term price variation and the VRE curtailment. Under the assumption made in the model, it has been shown that despite the minor impacts which DR has on the average price and on the end-users' costs, it may be very efficient in providing system benefits. Therefore, there might be needed specific policy instruments to motivate response at the consumption side. Also, it has been concluded, out of the model's assumptions and results, that for power systems in which thermal power has a large share of the base-load capacity, increase in DR may cause increase in the GHG emissions.

6.2 Fulfillment of goals

As outlined in the introduction chapter the PhD work should aim to fulfill the following two goals:

1. *Contribute to the decision-making processes within the company responsible for the project by describing probable market impacts of regulatory and technological changes.*
2. *Provide a scientific contribution to the field of energy system analysis by applying different modeling tools to define and quantify these impacts.*

When it comes to the fulfillment of Goal 1, the PhD work has significantly contributed to improving the decision processes at the employing company. As the company delivers its software product to market actors that operate in the balancing, the end-user market and the spot market, it has been important for it to gain insight into the pending market changes and their probable impacts. The company has power producers, BRPs and electricity retailers among its customers and the results and analysis provided in this thesis are considered to be of help when designing a competitive software product, adjusted to the customers' future needs. The topics and analyses to support the company's product design and decision-making are outlined below:

- The NBS model and the impact that a possible increase in the volume of regulating bids may have on the balancing prices for up- and down-regulation

- The establishment of a common Nordic end-user market for electricity and the impact of increased competition on the electricity retailers' strategies – in particular on their price and service decisions
- The role of smart grid technologies for improving retail offers and enabling DR
- The importance of DR for providing system benefits and its capability to improve the integration of VRE and increase the profits for the using RES power producers, which represent a considerable share of the company's customers

Regarding Goal 2, the work presented in the PhD study can be regarded as novel for the following reasons:

In the thesis the analyses are related to future power market changes - market integration, smart grid and increased usage of VRE in the generation mix. Investigating the effect that increase in the volume of regulating bids may have on the balancing prices for up- and down-regulation, this study contributes to previous literature on power balancing. While earlier studies have been discussing other balancing market related topics (as described in Section 2.2.1), this analysis focuses on the dependency between the regulating price and the volume of regulating bids through an econometric estimation. The study on the probable economic effects of an NBS model (Paper I) has been motivated by the work of Skytte (1999) in which the focus is on the pattern of prices in the regulating market and where a model of a similar functional form is used. However, the model applied in Paper I is distinguishable from that in Skytte (1999) in its presentation of the bids volumes, its temporal frame and its spatial resolution. Further on, the carried research on the balancing market prices can be related to the work of Boomsma et al. (2014) where the bidding problem faced by BRPs is presented as a multi-stage stochastic program through which it is investigated whether higher exposure to risk may cause hesitation to bid into the balancing market. Thus the volumes of bids may be affected as the share of intermittent renewable energy in the system increases and in this regard a realistic estimation of the "regulating price-regulating bids' volume" dependency could be a valuable resource.

The methodological approaches through which increased competition, electricity retailers' strategies (specifically their price to service preferences and profit expectations) and smart metering are simultaneously accounted for represent the novelty of Papers II and III. In addition, in Paper III the use of MCP to solve together the optimality conditions of rival retail firms is a contribution to both previous end-user market analysis, as well as to the wide variety of previous applications of MCP. Although the model simulations in the two studies are based on a number of assumptions and use a simplified two-retailer scenario and data for Norway, the results they provide give useful insight into what might be expected of retail market developments. Papers II and III contribute scientifically to previous research in the retail market field by focusing on the price and service strategies electricity retailers are to choose within a highly competitive and smart grid dominated end-user market. In this way the two studies, discussing the economic impacts of Nordic retail market integration and smart grid development, differ from earlier literature that also focuses on the Nordic region, such as Littlechild (2006), Amundsen and Bergman (2006), Amundsen and Bergman (2007). The last are predominantly answering general questions related to the Nordic retail markets – e.g., the benefits of retail competition.

The scientific contribution of Paper IV is related to the improvement in the Balmorel model and to the novelty of the results. The applied version of the Balmorel model is substantially improved (as compared to its preceding versions). In particular, the improved version includes a detailed modeling of the Norwegian and Swedish hydropower systems. Since very few power market models are suited to model both thermal and hydropower dominated systems, the applied in Paper IV version of Balmorel has its value from methodological viewpoint. As far as the novelty of the results are concerned, Paper IV finds relatively small price effect and a worrying result that increased DR might increase emissions, at least in the short run. The last result is, however, sensitive to the underlying assumptions on fuel and carbon prices. In addition, the study quantifies the system benefits associated with increased DR and reflects on how these will be of help for integrating VRE generation on a large scale. Finally, the results are seen as a part of a future power system the characteristic of which may change. Model simulations, for which the main assumptions have been varied, show that the benefits of DR are generally larger if there are tight supply-demand situations in the power system. Equilibrium models for power system modeling have been used, among others, in the works of Kudelko (2006), Huppmann and Egging (2014); and in the ones by Walawalkar et al. (2008), Choi and Thomas (2012) - for modeling of DR. Yet, in these studies the models applied are less detailed, have limited ability to model simultaneously thermal and hydropower systems and have different focus when it comes to the DR impacts.

It should be noted that the methods applied use specific regional resolution, and all four papers to build up the thesis include the Nordic region (although the regional subdivision differs from paper to paper). The efficiency of the Nordic market model has been confirmed by Amundsen and Bergman (2006). The Nordic region has a foremost position in market integration initiatives, use of VRE and is actively participating in research and development activities related to the smart grid. Therefore the trends and analyses presented in this PhD work can be of benefit to research activities in other regions.

To summarize, the papers should provoke research interest for several reasons. First, the papers use a variety of modeling tools to investigate problems on which research focus has so far has been limited: price elasticity at the Nordic balancing power market; electricity retailers' behavior in a highly liberalized end-user market where smart grid plays an increasing role; the impact of increased demand flexibility within a system with high degree of regulated hydropower and increasing shares of variable renewable energy. Second, they all focus on the Nordic region (Paper IV includes other countries in Northern Europe as well). And the Nordic region is in itself an interesting object for power system research due to its highly liberalized electricity market, high level of renewable generation and high number of smart grid initiatives within the power sector. Third, the models can be further developed and used as a basis for future research related to the Nordic balancing and retail power markets, smart grid and smart metering, and demand flexibility.

6.3 Key assumptions and policy implications

The analysis carried in this PhD study is based on a set of detailed assumptions which have been specified for each paper. This section briefly discusses some overall key assumptions made in the thesis.

Generally, this thesis takes a rather optimistic stand regarding smart grid implementation. In particular, the deployment of smart grid is considered fully accomplishable and is expected to provide system benefits through facilitating demand response and to allow for improved retail service. Albeit strong, this assumption is helpful when analyzing probable future power system developments.

Another important assumption is related to smart metering/smart grid technology as a facilitator for demand response and increased price elasticity of electricity demand. Within a low-price regime customers may be indifferent to changes in price (a basic assumption for the analysis in Paper IV), but rather be motivated by the possibility to have wider choice of power products and services (as suggested in Paper II and III). In reality, the change in end users' electricity consumption can be triggered by other than price factors. As an example, the study of Smith and Hledik (2011) applies statistical analysis and shows that in addition to its dependency on the electricity retail price, demand response is correlated to the following drives:

- Electricity market structure – in general, regions with deregulated electricity markets and high degree of retail competition have higher levels of DR
- Presence of demand-side policy regulation – both regulatory actions that directly support DR and legislations in favor of energy efficiency measures motivate high DR levels
- Generation mix – DR might be less attractive for regions with high amounts of regulated hydropower in the generation mix
- Reserve capacity margin – DR is capable of alleviating short-term stringency issues in the grid and has usually higher levels in regions where the reserve capacity margins are lower

Next, this PhD work takes a rather traditional vantage point as to what is the structure of the power sector, which market actors operate in it and how are these organized. The development of smart grid technologies can lead to changes in the electricity market structures, where the role of the discussed in this study market actors (TSOs, DSOs, retailers and producers) is revised completely. As an example, electricity end-user cooperatives and prosumer[10] communities have emerged (Bürger Energie 2015; Timmerman 2014). This proves that a combination of drivers (e.g., smart grid technology, policy regulation, end-user knowledge) could motivate the establishment of unique business models. In addition, as noted by Römer et al. (2012), there might be new market entrants to benefit from the new business models, as well as from bundling and coordination of power consumers, enabling of value-added services and special offers from niche players. The role of these new entrants is expected to increase in tact with technological improvements and increasing customer knowledge. It is hard to know if the "newcomers" will seize part of the business of the traditional market players that this thesis focuses on.

With reference to the studies' results and the above stated assumptions, the main policy implications of this works' findings could be summarized in the following points:

i. As discussed in Paper IV, increased DR contributes to only modest economic benefits for the consumers. Therefore, efficient policy instruments are likely needed to motivate flexible consumption. These policy instruments should consider that it is often the total value and total cost associated with DR measures that are the drivers for end-users, rather than only the cost of electricity.
ii. Stringent situations in areas with tight supply demand balance could be eased with help of market integration and increased DR. Paper I indicates that with the assumption for an increase in the volume of bids, consequent to an NBS model, the balancing prices for both up-

[10] The International Energy Agency defines prosumers (within the electricity industry) as energy consumers who also produce their own power from a range of different onsite generators (e.g., wind turbines, solar photovoltaic and combined heat-and-power systems) (IEA 2014).

and down-regulation could be lowered in areas where large amounts of regulation is needed. And Paper IV indicates that DR can improve balancing by reducing the annual and daily residual demand.

iii. Legislative initiatives to regulate the electricity retail market should consider the two-fold effect of increased retail competition within a smart grid environment. While, in general, improved retail service offers may push the price mark-ups higher (as presented in Papers II and III), the integration of demand response services in the retailers' portfolio of offers might work in the opposite direction, reducing the short-term price variation (Paper IV). Thus, to successfully implement policy measures within the end-user market, policy makers should also be well acquainted with the specific customer attitudes, as well as have realistic expectations on whether new market entrants will go for delivering electricity retail services to the end user.

6.4 Methodological limitations and further research

The methods applied in this study have some major limitations. These are related to the assumptions made when designing each model and concern specifically the models' scope and size. By methodological limitations related to "scope" are meant factors that could change (and likely improve) the overall model structure (e.g., additional independent variables to impact the balancing prices (Paper I), sensitivity parameters, number of retailers and different approach to service (Papers II and III), generation and storage technologies and availability of VRE (Paper IV)). The limitations related to "size" concern the models' spatial and temporal restrictions, such as: countries, regions and areas included in the models; size and age of the historical data used; temporal resolution of the models' results. In this regard, the results presented in this thesis should be always interpreted in the context of the underlying assumptions and be considered only suggestive for the possible future power system developments. However, the applied models have the potential for further improvements that could set aside part of the methodological limitations discussed. Some important steps to improve the modeling procedures and their relation to further research are discussed hereby.

The possibility for further research with respect to Paper I could be related to a model extension so that the BRP's market strategies are incorporated , in line with the research by e.g., Skytte (1999) and Boomsma et al. (2014). The elasticity values presented by the model could be differentiated to groups of BRPs with certain market strategies/risk preferences. In this way the bids' volume effect on the prices for up- and down-regulation would vary not only across seasons and regions, but also with respect to the BRPs' market strategies and the results could provide deeper insight on the actually expected price changes. More analysis related to the choice of econometric estimator, especially related to possible simultaneity, is another field for future research.

In the model simulations in Papers II and III a simplified two-retailer case is used. Yet, the models in both papers can be successfully adapted to a larger number of competitors. The MCP where n rival firms compete in the market is presented in the Appendix of Paper III. The two studies on retail market integration use different approaches when quantifying service – values for hourly investment in service and a system of weight points. In addition the used in the model simulations data for the retailers' market base and service level is specifically for the Norwegian retail market. Thus, when it comes to Papers II and III, further research could be related to a more extensive data collection and model expansion, such as: use of data from a larger region when modeling service level and describing retailers' market base; applying updated values for the sensitivity coefficients; extending the model to larger number of competitors. The presented in Paper II and III market developments are indicative for what might be the future trends within a highly competitive common end-user market, but the use of purely Norwegian data in the model simulations and the two-retailer case set limit to the more realistic presentation of the future integrated Nordic retail market. Including all Nordic countries and increasing the number of competing firms could, therefore, deepen the knowledge on retailers' strategic behavior and the expected retail market developments.

The applied in Paper IV Balmorel model is a deterministic one. This could be considered a limitation for modeling hydro dominated power systems as well as for modelling the intermittent characteristics of VRE. Seljom and Tomasgard (2015) model the intermittency of wind power through a stochastic parameter in a long term TIMES model representing the electricity and heat sector in Denmark. Their findings suggest that stochastic representation of VRE should be considered the better alternative. Yet, from an energy system perspective, the benefits of a highly detailed modeling can be regarded as more important than the possible gains of including uncertainty. Modeling uncertainty in i.e., wind power production would be relevant for dealing with forecast errors in production and could be the focus of further improvements in the Balmorel model. A more detailed discussion on the shortcomings in the modeling approach is provided in Section 6 in Paper IV.

Also, as discussed by Hedegaard (2013), the lack of quantifying the changes related to ancillary services when using the Balmorel model can be corrected for by applying a two-step approach. Such an approach would reveal the effects on energy system investments in a first step – e.g., with the help of Balmorel. Then, in a second step, the optimized energy system configuration is used as an input when analyzing the effects on system operation in another model. Hedegaard (2013) suggests the Wilmar model as an appropriate one for the second step and refers to Kiviluoma and Meibom (2011) where the approach has already been applied.

Finally, the key assumptions described in Section 6.3 above set additional limitations on the methods applied. In particular, the models do not consider the possibility for new market entrants and new market models, and in none of the models used for the analysis the behavior and attitudes of end-users are accounted for. And not less important, the analysis only scarcely reflects on the costs associated with smart grid penetration and demand response. Considering the model limitations discussed above, the results presented in the study should be regarded as approximations to the expected market impacts and as suggestive for the trends in power market development.

In general, this PhD thesis provides a hint to the future power market developments, by applying a diversified set of modeling approaches, each of which has the possibility for further extension and calibration with updated data. In this way, augmented and improved models can assist the future decisions of power producers, electricity retailers, TSOs, policy makers and external companies that are to sell power market related products within a smart grid dominated power system.

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Appendix

Paper I: An econometric analysis of the regulation power market at the Nordic power exchange

Paper II: Electricity retailers' behavior in a highly competitive Nordic electricity market

Paper III: The impact of end-user market integration and smart grid on electricity retailers in the Nordic region

Paper IV: Electricity market impacts of increased demand flexibility enabled by smart grid

Paper I

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Energy Procedia 58 (2014) 58 – 64

Energy Procedia

Renewable Energy Research Conference, RERC 2014

An econometric analysis of the regulation power market at the Nordic power exchange

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Abstract

Increasing shares of variable renewable energy (VRE) causes challenges related to power system balancing. The regulating power market is part of the Nordic electricity market and has as purpose to maintain the balance between total generation and consumption of power in real time. Currently, the power balance settlement is being carried on a national level, by the separate transmission operator in each Nordic country. Recent developments, in the form of a common project initiated by the system operators in Norway, Sweden and Finland, attempt to change the routinized course of the balance settlement by introducing a model for common Nordic balance and reconciliation settlement (NBS). The regulatory change will make the rules for balance settlement equal to all Nordic participants, ease market participation and possibly increase the number of smaller market actors. For power market participants it is of interest to analyze how the regulatory change will affect balancing market prices. This paper analyzes how the regulating price in different price areas in the Nord Pool region is affected by the level of the spot price and the volumes of regulating bids using historical market data. According to the estimated econometric models, the down-regulation price is more sensitive to the regulating volumes than the up-regulation price. At maximum the up-regulation price decreases by 0.14% as a result of a 1% increase in the bids' volume, while for the down-regulation price a greater than 0.2% increase is observed. Also, the results show relatively large differences in the sensitivity of spot prices and bid volumes across different areas and seasons.

Peer-review under responsibility of the Scientific Committee of RERC 2014

Keywords: Balancing market, market integration, regulatory changes, Nord Pool

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Peer-review under responsibility of the Scientific Committee of RERC 2014
doi:10.1016/j.egypro.2014.10.409

1. Introduction

The purpose of the Nordic regulating power market is to maintain the balance between total generation and consumption of power in real time. It is managed by the transmission system operators - TSOs (Statnett in Norway, Svenska Kraftnät in Sweden, Energinet.dk in Denmark and Fingrid in Finland). The balancing capacities traded in this market are known as tertiary reserves or regulation power reserves and are mainly manually activated [1]. Electricity retailers buy power at the wholesale market based on estimates on how much electricity their clients will consume. If the estimated figures deviate from the actual ones they should either per definition sell excess power to the system operator (in the case when customers have used less than expected) or buy power from the system operator (when customers have used more than expected).

Balancing power needs also to be settled between producers and TSOs when producers fail to produce according to the plans. The existence of a balancing market ensures that producers that have difficulties to fulfill their commitments to the spot market but have no flexibility in generation can meet those who can rapidly regulate their production. This happens through the market mechanism with up- and down-regulating prices and helps keeping the balance between supply and demand in real time. The deviating amount of electricity that is to be settled between the TSOs and the retailers/producers is called balancing power[2].

Although the market participants are making their offers to sell and bids to buy at the common Nordic power exchange, the power balance settlement is being currently carried on a national level, by the separate transmission operator in each Nordic country. Recent developments, in the form of a common project initiated by the system operators in Norway, Sweden and Finland, attempt to change the routinized course of the balance settlement by introducing a model for common Nordic balance and reconciliation settlement[1] (NBS). The model developers describe the model as one in which a common Nordic body called settlement responsible (SR) is responsible for the balance settlement, invoicing and collaterals towards the balancing responsible parties (BRP)[2]. The settlement responsible, for which decision has been taken to be established in Finland, should carry on all these activities on behalf of the transmission system operator in each country [3].

Implementing the model is expected to ease the settlement procedures as there will be only one counterpart in the face of a common Nordic settlement responsible unit, as well as reduced amount of communication between the distribution system operators and the BRP. Laws and regulations will be harmonized, the complexity for BRPs to operate in a Nordic scope reduced and the entry barriers for new participants lowered.

The literature on balancing market has so far been focusing primarily on its operational side. The works of Vandezande et al. [4] and Sorknæs et al. [5] focus on the effects of wind power generation on the balancing market, while Van der Veen and De Vries [6] analyze the possible impact of an increasing share of household and small business microgeneration technologies on the Dutch balancing power market. Scientific work has also been devoted to the enhancement of a larger regulating power market in Northern Europe. Such an example is the research carried out by Farahmand and Doorman [7] and Jaehnert and Doorman [8]. The work of Skytte [9] focuses on the pattern of the prices on the regulating market and as such stands closest to the research presented here. Skytte investigates the regulating power market considering the costs associated with the inability of market actors to comply with the commitments made at the spot market. Clearly generators with fluctuating production participate in the power exchange on the same conditions as those producers that can regulate their generation and always comply with the offers made. This fact questions the strategy that producers with fluctuating generation may have under the bidding process as they will have to take into account the cost for up- or down-regulation they have to carry. Skytte defines the cost associated with using regulating power as a quadratic function of the amount of regulation and indicates the possibility for aggressive bidding strategy on the spot market as a consequence of this asymmetric cost.

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[1] With reconciliation settlement is meant the settlement method that takes into account the differences between consumption that has been preliminary profiled for the purposes of balance settlement and finally profiled consumption.

[2] Balancing responsible parties are considered those power market players that have agreements with the system operator to buy or sell market power in order to neutralize grid imbalances.

Despite the fact that various aspects of the balancing market have been examined in the literature so far, no one has analyzed the regulating power market in the Nordic countries, to our knowledge. As noted by Skytte [9], the relationship between the prices in the spot and regulating power market is of particular importance for agents in the market that has unpredictable, fluctuating supply and demand, like e.g. variable renewable energy (VRE). And a Nordic study is of particular interest with the prospects of a common balance settlement model in the Nordic region. The objective of this paper is to analyze how the spot price and bid volumes affect the regulating power prices, i.e. the costs of being unable to fulfil the commitments made on the spot market in the different Nordic countries. For the purpose will be used historical data available from the Nord Pool Spot database. Considering the new developments in the regulating market as defined in the NBS model, the possible effect of an increase in the volume of regulating bids on the balancing market prices will then be investigated. Also, the differences between estimation results with respect to generation mix in the separate country and seasonal variations are discussed.

2. Econometric model and data

Following the study of Skytte, [9], the following functional form will be investigated:

$$P_r = \sigma_0 + 1_{V>0}(\alpha P_s + \beta V + \eta) + 1_{V<0}(\gamma P_s + \delta V + \mu) \tag{1}$$

In the equation (1) P_r presents the regulating price, P_s is the spot price, and V is the volume of regulating bids. In the case where V is positive the equation will be estimated for up-regulation and P_r will actually represent the up-regulating price, and V is the volume of up-regulating bids. Respectively, when V is negative the equation will be estimated for down regulation with P_r then being the down-regulating price and V – the volume of down-regulating bids. The multiplicator of 1 serves as an indicator and equals zero if the statements about the value of V are false, and σ_0 is the constant term.

The coefficients α and γ represent the relation between regulating and spot prices, while β and δ define the dependence of regulating prices on the up- or down-regulating volumes of bids. In his work Skytte [9] analyzes an equation of a similar functional form and describes these coefficients as the "marginal regulating power prices per unit of regulated power". However, in his study the independent variables used are the spot price and the total amount of regulating power activated, and not the volume of bids. In this case β and δ will be the marginal prices per unit of regulating bid, thus providing a different application of Skytte's functional form. To complete the econometric model the error terms η and μ are added to respectively the equation parts for down and up regulation.

The data used in the model represents time-series for the six-month period: 1 January 2012 to 30 June 2012. The time series comprise hourly data taken from Nord Pool Spot database and includes all the price areas in the Nordic countries Sweden, Finland and Norway. This corresponds to a total number of 4368 hourly observations for each variable in the model. The analysis is based on three main groups of variables: regulating prices, elspot prices and volumes of regulating bids. Here by "groups" is meant the division in bidding areas within each variable (five bidding areas in Norway, four in Sweden and one in Finland).

The functional form (1) could intuitively raise questions of endogeneity. However, since the market spot price is being decided prior to the clearing in the regulating market, it seems reasonable to assume that the spot price is determined independently of the regulating price. Second, the volume variable in the equation consists of the total volumes bid at the market, not the market clearing volumes, and is thus also assumed to be independent from the regulating prices. Hence, in similarity to the approach of Skytte [9], we assume that the two right-hand side variables are determined independently of the regulating price.

3. Estimation results and discussion

To conduct the econometric analysis the program Stata is used. Before the estimation work starts stationarity of the time series is being confirmed using the Dickey-Fuller test. At a next step equation (1) is estimated for each of the price zones, the variables being transformed in logarithmic form to find elasticity values. A summary of the results is presented in the table below; all the coefficient estimates (except the ones in brackets in Table 1) are statistically significant at 5% significance level.

Table 1 – Constant term and estimated coefficients on equation (1)

Constant term/Coeff.	NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4	FI
$\sigma_0\ (up)$	0.3894	0.2997	-0.1134	0.4292	-0.3013	0.5080	0.1221	0.0555	-0.0557	0.8382
$\alpha\ (P_s)$	1.0093	1.0103	1.0857	1.0025	1.1020	0.9698	1.0415	1.0855	1.0984	1.0887
$\beta\ (V_{up})$	-0.0502	-0.0359	-0.0177	-0.0569	(0.0014)	-0.0548	-0.0357	-0.0393	-0.0333	-0.1412
$R^2\ (up)$	0.8287	0.7864	0.7701	0.7673	0.8151	0.7780	0.7464	0.7662	0.7347	0.6334
$\sigma_0(down)$	-0.7598	-1.6043	-1.7193	-1.2625	-1.9352	-0.6023	-1.1637	-0.3706	0.8073	-0.2930
$\gamma\ (P_s)$	1.0185	0.8414	0.9848	0.9003	0.9737	1.1153	1.0369	0.9783	0.6638	1.0496
$\delta\ (V_{down})$	0.0790	0.2409	0.2267	0.2146	0.2590	(0.0039)	0.1330	0.0561	0.0791	(-0.0108)
$R^2\ (down)$	0.6407	0.6260	0.6276	0.6464	0.6350	0.6067	0.6345	0.6205	0.5707	0.6003

3.1. The impact of changes in the spot price and in the volumes of regulating bids on the balancing price

All significant coefficient estimates on β (negative elasticity values) indicate a slight decrease in the price for up-regulation as a result of an increase in the volumes of up-regulating bids. The highest value for percentage decrease in the up-regulating price is for Finland (-0.14%), followed by NO2, NO4 and SE1.

To examine the elasticity of down-regulating prices with respect to regulating bids, the estimation values of δ are to be analysed. For price areas NO2, NO3, NO4 and NO5 the coefficient estimates indicate greater than 0.2% increase in down-regulating price as a result of a 1% increase in the volume of bids for down-regulation.

It seems like the sensitivity of the down-regulating price with respect to an increase in the regulating bids' volume is higher than that of the up-regulating price. The observed trends are different from the ones provided by Skytte [9], who concludes that the amount of balancing power affects the up-regulating price more strongly than it does for the down-regulating price. However, as previously mentioned, Skytte [9]considers the total amount of regulation, while this article focuses on the specific volumes of up and down regulation bids. In this respect, the different results are not contradicting, but rather complementing each other.

The option for easing accessibility to the balancing market in the form of a common balance settlement could be a key motivating factor for increasing the volumes of the bids. Making the rules for balancing settlement equal to all Nordic participants might be particularly important for the smaller actors that so far have been prevented from participation due to the complexity in the settlement procedures, and one could expect larger volumes from these actors in a common Nordic market. Yet, it is important to notice that the estimated elasticity values are only valid for the regulating bids (V) data selected for the model. Big changes in the volume of bids could alter the effects, but our aim here is to detect the regulating price trends associated with a potential increase in V.

For the coefficient estimates on the spot price it can be seen from table 1 that a 1% increase in the spot price increased the price for up regulation with more than one percent in all cases except for SE1 in our data. On the contrary, such a generalized conclusion cannot be derived for the elasticity of the down-regulating prices with respect to spot prices. Here the increase in spot price by 1% leads to an increase in the price for down-regulation with a bit less than 1% in most cases, but with more than 1% for NO1 and SE2. Yet, on average, the sensitivity of the regulating prices due to change in the spot price was found higher for the up-regulating prices than for the down-regulating ones.

With technological advances in the smart grid field, it will become easier for market actors to utilize flexibility in consumption as a balancing power resource. Active electricity suppliers or actors of the type "energy system company" that choose to take the role of an aggregator could make profit by bidding their customers' aggregated flexible loads on the regulating power market. Despite the existing requirements for activation time and size of the bid, innovative techniques for communication and measuring, combined with the integration in the settlement procedures, will make possible the participation of new market actors in the balancing power market. In addition, the estimated elasticities may experience significant changes in the future as more end-user flexibility enabled by smart meters is added to the power system. As a result the need for balancing power can be reduced: a fact that will influence both bidding volumes and balancing prices.

3.2. Differences between countries

From table 1, it can be seen that the regulation price in Finland is most sensitive to changes in the volumes of bids for up-regulation. When it comes to the down-regulating price elasticities, it is the Norwegian price areas NO2, NO3, NO4 and NO5 that exhibit highest values (Figure 1). However, these are not the price areas where the greatest volumes of regulating power are being traded. Instead the areas SE1, SE2 and NO2 are the most dependent on up- and down- regulation (Figure 2). Thus there could be other factors that determine how strongly the regulating prices depend on the volumes of regulating bids in a given area - such as bottlenecks in transmission, or availability of longer-term contracts for delivery of balancing power (such as options or bilateral contracts).

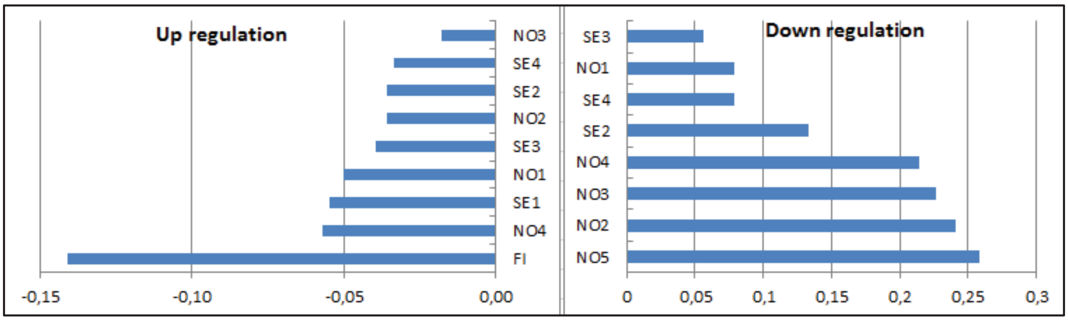

Figure 1 – Elasticity of regulating prices with respect to regulating bids' volumes in the different price areas.

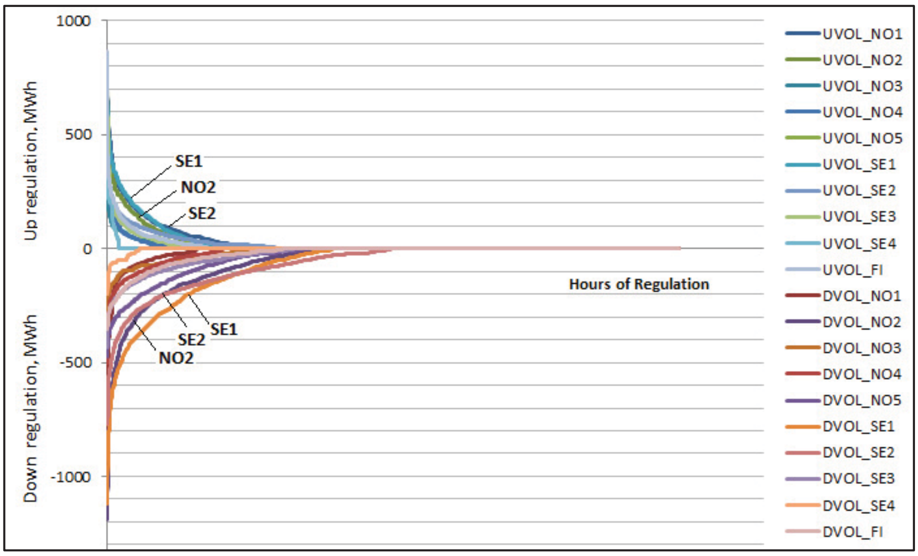

Figure 2 – Up and down regulation during the six month period - sorted by volume for each hour

Further we aim to investigate if the differences in the production mix between countries can be related to the elasticity values obtained from the model. In general, the electricity production in Norway is based on hydro power and in Sweden it is dominated by hydro and nuclear power. Finland gets almost one-third of its electricity generated from nuclear power while the rest of the production is a combination of hydro power, natural gas, hard coal, wood fuels and peat. Considering these country-specific production mixes, we could find some parallels to the estimation results presented in Table 1.

The impact of increase in the volumes of down-regulating bids on the down-regulating price, as measured by the coefficient δ (V_{down}) in Table 1, is highest for Norway (Price areas NO2 to NO5). This finding is probably caused by periods with extraordinary high water flow levels (typically during snow melt), where the unregulated hydro production is very high and rather unpredictable. These circumstances will typically cause quite low down regulation prices. The elasticity of up-regulating prices with respect to the volumes of up-regulating bids is highest ($\beta(V_{up})$ = -0.14) for Finland where there is least amount of hydro power in the generation mix and a wide range of other generation technologies are being used.

Regarding the relation between the spot and the regulating prices in each country, no clear trend that parallels the production mix can be discovered. The dependences at this point are rather related to the separate price areas, and not to the countries. The price area NO5 is the one for which an increase in the spot price will cause a highest increase in the up-regulating prices ($\alpha\ (P_s) = 1.1$). This region (the Bergen area) was established in 2011 as a consequence of an extraordinary tight supply-demand situation. The high α parameter is as such not surprising.

Among the spot price elasticity values for down-regulation, the lowest is that for the price area SE4 ($\gamma\ (P_s) = 0.66$). SE4 is the Northern Sweden having a large share of run-of-river hydro power and relatively limited demand.

The importance of the NBS model is expected to increase as more VRE (e.g. wind) is added to the power system. Currently all the participating countries have plans to increase this type of electricity production in nearest future. A common model for balance settlement and reduced prices for up-regulation can benefit power plants that run on intermittent renewable resources and motivate for further investments.

3.3. Seasonal variation

To capture the impact of seasonal variation we run the regression model with data for the second and sixth month in 2012. The following results are obtained for the different price areas:

Table 2 – Estimation results per price area, averaged data for February and June 2012. Estimation coefficients that are not significant at the 5% significance level are presented in brackets.

	Coefficient	NO1	NO2	NO3	NO4	NO5	SE1	SE2	SE3	SE4	FI
February 2012	$\alpha\ (P_s)$	0.9913	0.9950	1.1424	1.0625	1.150871	0.8910	1.1265	1.1382	1.0211	1.0251
	$\beta\ (V_{up})$	-0.1251	-0.0974	-0.0598	-0.0936	(-0.0465)	-0.1041	-0.0299	0.2234	0.3886	-0.3833
	$\gamma\ (P_s)$	0.7218	0.6317	0.7462	0.7567	0.6585	0.8339	0.7451	0.7819	0.6403	0.7285
	$\delta\ (V_{down})$	0.0959	0.1851	0.2314	0.1225	0.5013	-0.0198	0.1914	(0.0286)	0.0955	0.0757
June 2012	$\alpha\ (P_s)$	1.0405	1.0571	1.1947	1.1724	1.0067	0.9286	0.9967	1.0756	1.0260	1.1463
	$\beta\ (V_{up})$	-0.0320	(-0.0115)	0.0892	0.0479	(0.0028)	-0.0801	-0.0304	-0.1757	-0.1359	(0.0049)
	$\gamma\ (P_s)$	2.0519	1.9587	1.2169	1.6348	2.2123	1.4763	1.2924	1.0911	0.6903	1.2715
	$\delta\ (V_{down})$	(-0.0020)	(0.0172)	0.3615	(-0.0653)	-0.2590	-0.0714	0.2745	(0.0390)	0.1007	(-0.1096)

Although the differences in the estimation coefficients are small, some seasonal patterns can be observed. The elasticity values presented by $\alpha\ (P_s)$ indicate that the impact of spot prices on the up-regulating prices varies between months and price areas. However, the results do not show any clear trends of differentiation between the seasons – for some price areas the February price elasticity values are lower than the June values, while for other they are higher. It should be noted that the 2012 winter had somewhat higher temperatures than the normal, and that the hydro power balance (hydro storage) was above normal levels.

The case is different when the model is run for down-regulation. The summer spot price elasticity values $\gamma\ (P_s)$ are significantly higher for all price areas. Thus an increase in the spot price during the summer months will cause greater percentage increase in the down-regulating price than it will during the winter time. One explanation could be that in the summer months balancing parties have more free capacity, and would rather trade in the spot market than reduce production to make profit in the balancing market.

Regarding the volume of bids, no specific patterns in the seasonal elasticity values can be discovered. The differences are rather concerning the different price areas, and not the monthly variations as a whole. For example, the NO5 volume of down-regulating bids coefficient ($\delta\ (V_{down})$) is positive for February and negative for June. Yet, the estimated NO5 coefficient for the whole period is positive (($\delta\ (V_{down}) = 0.2590$ in Table 1). For price areas with typically higher amount of down regulation needed (total regulation amount for the period: 161,804 MW/h for NO5 versus 51,886 MW/h for NO1), the increase in the volume of down-regulating bids could actually decrease the down-regulating prices during the summer periods when more free capacity is available.

4. Conclusions

Regulative changes directed towards increased power market integration in the Nordic region will also affect the balancing market. The TSOs in Norway, Finland and Sweden are cooperating on the development of a model for common Nordic balance settlement that is to be operational from 2015. One of the main benefits associated with this model will be lower entry barriers for market actors willing to offer balancing power. Using the tools of regression analysis the possibility for increase in the volume of bids for up and down regulation and their impact on the balancing prices have been examined in this study. The estimation results indicate a slight decrease in the price for up-regulation as a result of an increase in the volumes of up-regulating bids (at maximum 0.14% as a result of a 1% increase in the bids' volume); and greater than 0.2% increase in down-regulating price. The sensitivity of the down-regulating price with respect to an increase in the regulating bids' volume has been proven higher. The establishment of a common Nordic balance settlement regime could strengthen the significance of this fact. Making the rules for balance settlement equal to all Nordic participants might be particularly important for the smaller actors that have been so far prevented from participation due to the complexity in the settlement procedures. Possibly the increase will be significant for the smaller in size up- and down-regulating bids, thus contributing for lower up-regulating and higher down-regulating prices.

In the regression model both the spot price and the volume of regulating bids have been used to determine the changes in the regulating price. The estimation results indicate that the impact of the spot price can vary between price areas and seasons. One example is that an increase in the spot price during summer months has proven to cause greater percentage increase in the down-regulating price, than it will during winter time. Thus the actual regulating prices and the associated elasticity values in the future will be dependent on the amount of VRE in each area, the season, the level of flexible demand, and also (as suggested by Skytte [9]) the BRPs' market strategies. Yet the results in this work can be considered indicative for the expected adjustments in the balancing price associated with a NBS regime.

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Paper II

Journal of Energy Markets **7**(4), 17–46

Electricity retailers' behavior in a highly competitive Nordic electricity market

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(Received September 24, 2013; revised July 3, 2014; accepted July 21, 2014)

The integration of the national electricity retail markets in the Nordic region is expected to intensify competition among retailers. At the same time, technological developments will make possible the creation of a smart electricity grid that includes smart meters, two-way communication and real-time pricing. With the help of smart-meter technologies, retailers will be able to significantly increase the range of their service offers, allowing customers to choose from a variety of retail products. We describe the present status of the Nordic retail market for electricity and discuss the likely impact of a pending regulatory change to the common Nordic end-user market based on the functionalities offered by smart metering. In particular, we investigate the effects on competing retailers' profit, price markup and service investment by formulating a nonlinear program and solving it for numerical values that have been calibrated to be close to reality. The results from model simulations for a two-retailer case indicate that price and service decisions made by one retailer have a strong impact on the market strategy of the other. The range of this impact depends on the overall level of price markup values.

1 INTRODUCTION

Recognizing both the market efficiency and the benefits of a larger market, some countries have chosen to work toward integration of their electricity sectors. The Nordic countries Norway, Sweden, Finland and Denmark became pioneers in this respect and constitute an excellent example of how far electricity markets can be integrated.

The Nordic countries have a long history of cooperation within the electricity market field. In 2000 the process of creating a common wholesale market comprising Norway, Sweden, Finland and Denmark was completed. This market endeavor has about 70% of the power generated in the Nordic countries traded in its power exchange. Yet, the harmonization work in the Nordic countries has not stopped with a well-functioning wholesale market. It has continued toward the retail markets, which are at present still only national in scope. This further harmonization is expected to contribute to better resource utilization as well as to result in a number of customer benefits.

In 2004 the Nordic Council of Ministers decided to unite toward a common Nordic end-user market for electricity in the so-called Akureyri Declaration (Morch 2008). The work on developing the end-user market model was delegated to the Nordic Energy Regulators (NordREG), which has investigated multiple aspects of the harmonization process and made plans to implement market integration. At the beginning of 2011 the project entered a phase of intensive development, with NordREG working together with more than 100 other electricity market participants to find an optimal model for the future Nordic end-user market (Nordic Council of Ministers' Electricity Market Group 2011).

The purpose of a common end-user market design is to allow customers to enjoy a free choice of supplier as well as efficient and competitive prices and reliable supply (Nordic Energy Regulators 2009).[1] End-user markets in Norway, Sweden, Finland and Denmark should be harmonized to such an extent that it is possible for electricity retailers to treat all Nordic countries, with the exception of Iceland, as a single region, where electricity consumers will be able to purchase electricity across national borders. In this respect, the process will require harmonization of the most critical market features related to regulation, business models and IT standards. However, no harmonization of the use of system charges will be needed, as the supply and the distribution of electricity are separate in the Nordic market. If the retail market integration does take place, the total market area will be of significant scope: approximately 1 155 000 km^2, 340 retail competitors, 23 million potential customers and 400 000 GWh per year.

As a result of the integration process, competition in the retail market is expected to increase. At the same time, technological development makes it possible for electricity retailers to offer a wider range of services, and retail competition in both price and service will likely intensify. In an integrated Nordic end-user market the combination of metering equipment and a wide variety of electricity supply contracts

[1] We use the terms supplier and retailer interchangeably.

(independent of the supplier's country of origin) will stimulate the customers to adapt their consumption behavior to the wholesale market prices across regions.

The main aim of this paper is to analyze an electricity retailer's strategy for active competition in both prices and service. We therefore use a simplified yet illustrative representation of the Norwegian retail market with two retailers who simultaneously compete in price and service. The retailer's aim is to maximize their expected profit. We observe the impact of variations in one retailer's price and service offers on the other retailer's profit and price and service strategies and draw conclusions on the retailers' behavior in a highly competitive and technologically advanced retail market environment. The two-retailer assumption helps the modeling procedures and also makes it easier to understand the effect of retail market integration when a higher number of electricity retailers are present.

The rest of this paper is structured as follows: Section 2 presents some key model assumptions; Section 3 contains a brief literature review; Section 4 describes the nomenclature and definitions of key elements in the model; Section 5 presents the mathematical model, with a focus on the objective function, constraint and feasibility of the solution; Section 6 provides the data used for model simulations; Section 7 contains the numerical results from model stimulations and a discussion on them; Section 8 summarizes the conclusions.

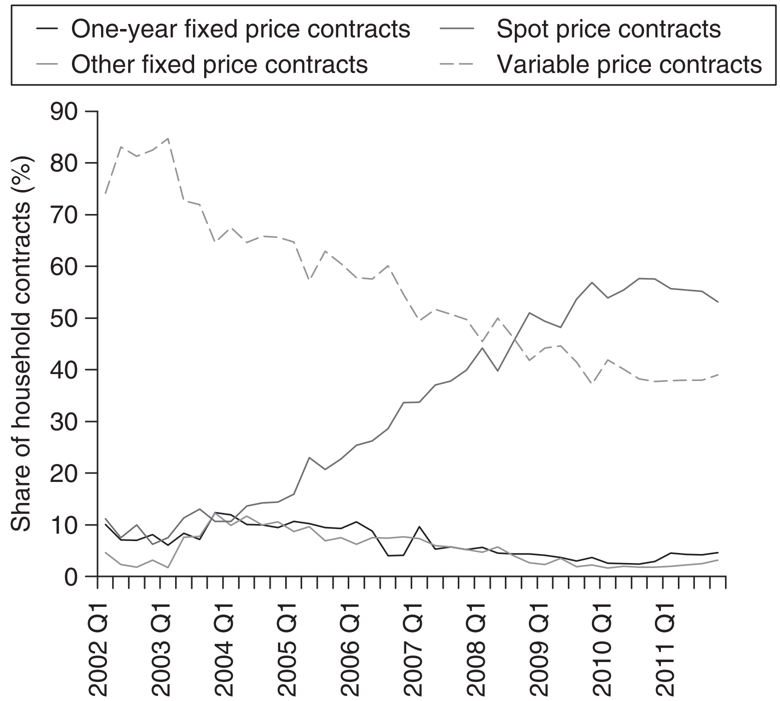
2 RETAIL MARKET SETTING: MAIN ASSUMPTIONS

2.1 Competition in price

A retailer competing in the Nordic market will have to make two important decisions: how to price electricity supply contracts and how much to invest in service, with the implicit assumption that the service level is monotonically increasing with investment. Service is a complicated term, various aspects of which we explain in Section 2.2. Here we focus on the pricing side in electricity retailers' strategies. Looking at the historical development in the Norwegian power retail market, we can observe a strongly decreasing trend in the variable price contracts and a huge increase in the spot-price contracts in the period 2002–11 (Figure 1 on the next page).[2] With the development of smart metering in the Nordic power sector, real-time pricing contracts, for which electricity consumption is priced instantaneously based on the cost

[2] There are three main types of electricity supply contracts in the Nordic retail market for electricity: fixed-price contracts, which keep the price of electricity fixed over a given period (one year or longer); variable price contracts, for which the price varies with the market price but there is a regulatory time lag of at least fourteen days for price changes to take place; and spot-price contracts, which follow the spot price from Nord Pool. A price markup is added to the market price before the customers are invoiced. However, only the average monthly spot prices are used for invoicing.

FIGURE 1 Share of electricity supply contracts for households in Norway.



Source: Ericson (2007).

of electricity as provided by the power exchange, may become a common choice. Currently, approximately 50% of all Norwegian households use spot-price contracts.

Judging from the trends presented in Figure 1, we might expect that the number of contracts connected to the power exchange spot price will continue to grow. Furthermore, the development and installation of advanced metering system technologies point toward an upswing in the spot-price contracts, making possible the transition from average monthly spot pricing (currently used in Norway) to hourly spot-pricing methods. Ericson (2007) discusses the possibility of improving the functioning of the electricity market through automatic meter reading and direct load control technology combined with time-differentiated prices. In his paper, pricing schemes that reflect the continuously varying cost of electricity consumption (as reflected in the wholesale prices) are considered essential for effective market operation, as they eliminate the disconnection between the wholesale and retail markets.

Taking into account the benefits from real-time pricing as discussed in the literature, we chose to use hourly resolution for our model. Retailers' contracts are therefore based on the hourly spot price as settled at the power exchange. The retailers' part in price setting will be limited to deciding on the own price markup. For Norway, the price markup is defined as the retailers' øre per kWh charge to customers for the electricity delivered to their homes.[3] This price markup is added to the hourly spot price together with taxes and comprises a very small portion of the total kWh price consumers pay for electricity (about 10–12%).

The price margins in the domestic electric power markets of Norway, Sweden, Finland and Denmark are small (Damsgaard and Römpotti 2007), indicating a low level of concentration, and make it hard to believe that competition will greatly increase with respect to the size of the price markups. This fact will stimulate innovative retailers to invest in service, forcing retail competition not only in prices but also in service. In marketing, this type of competition is often described as "competition beyond price".

2.2 Competition in service

Our starting position for describing the potential customer benefits associated with a common Nordic power market is the NordREG's market design decision on a supplier-centric model. Supplier-centric models comprise most European end-user market models. They are characterized by the retailer being responsible for invoicing both electricity supply and distribution and offering customer assistance. The distribution system operator is responsible for grid maintenance and connection to/disconnection from the grid. Under such a market model, the customers interact to the highest possible degree with the suppliers, and the role of power suppliers as providers of electricity-related services increases.

In a highly competitive electricity retail market, the fact that consumers like choice and that smart metering enables electric power to be combined with other products and services could gradually cause a renaissance in the service offerings of the Nordic electricity retail market. Facing an increasing number of competitors in a common Nordic end-user market setting, retailers may choose to promote new products to differentiate themselves.

Currently, electricity retailers' service is to sell electricity through predominantly fixed-price and spot-price contracts. When customers with spot-price contracts receive their monthly bills, they see tariffs that are calculated based on the averaged monthly prices and overall consumption. No consideration is made for the amount of electricity consumed during peak periods. With the installation of automated meter reading devices and the overall development of smart metering, it is expected that new possibilities will open up for the retailers. In a common Nordic end-user market, the offer of new services might be the key to a competitive advantage, and examples of such services are discussed next.

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[3] The øre is a currency unit equal to one hundredth of a Norwegian krone (NKr).

Flexible load

Retailers may develop innovative programs for buying consumers' flexibility (such as the flexibility of decreased or postponed heating of water and in-house space with electric heaters). Consumers could be rewarded for their flexibility through lower prices, or, for example, monetary bonuses, additional services such as home monitoring and security/alarm offers or free technology assistance.

Distributed generation management

Retailers who manage to take on the role of aggregator and buy and sell electricity from a number of distributed generation owners could gain advantage in the common Nordic market.

Electrical vehicle charging/discharging management programs

During the period September 2011 to September 2012, the number of electric vehicles in Norway increased by more than 50% to a total of 8581 vehicles. As the number continues to increase – the projections for Norway are 100 000 electric vehicles by 2020 (Norwegian Electrical Vehicle Association 2012) – and with the development of powerful batteries for longer distances, the owners of these vehicles will experience an increasing need for management during charging/discharging periods. In this respect, electricity retailers that offer services optimizing cost savings during charging and benefit when discharging could be preferred by owners of electric vehicles or hybrid plug-in cars. Such electric vehicle management programs will offer the option to link the cost of charging the battery to the hourly market prices and will be attractive to both the power retailers and their customers.

Variety of power-pricing schemes

With the improvement in technology for hourly metering, pricing schemes solely or partly based on real-time prices will be included in retailers' offers. Another possibility will be the introduction of dynamic tariffs, where customers pay different prices for electricity usage during blocks of hours throughout the day (eg, the Tempo tariff in France). As Zugno *et al* (2013) show, dynamic pricing schemes outperform both real-time tariffs and fixed-price tariffs when it comes to retailers' market participation and cost minimization. For the customers, real-time pricing is said to provide the least-cost option, but dynamic pricing remains more convenient.

Energy management programs

According to a recent study on end-user preferences (Accenture Research 2011), there are several types of energy management programs that are of significant interest to customers, including completely automated electricity management, usage monitoring and management through personal electronics (eg, smartphones, tablet PC), customized in-home displays and websites. For Norwegian vacation homes the option to secure an optimal heating level prior to the arrival of the owners or visitors is regarded as an attractive feature.

Energy audit and energy efficiency

Promotion of energy efficiency can be seen as a part of the retailer–consumer relationship and promotion of such efficiency programs might be a good solution for retailers that are under commercial pressure to retain customers. Retailers could perform energy audits and give advice on possibilities for savings. Or they could help customers to directly decrease electricity usage by providing installation and support for energy efficient appliances.

Go-green programs

Retailers in Norway (and throughout Europe) are already offering contracts that guarantee that the amount of electricity consumed by the customer is matched by that produced by renewable sources. As the consequences of global warming become increasingly evident, people worldwide are starting to act in an environmentally friendly way.

In addition to offering new services such as the ones described above, retailers who want to stay competitive will have to invest in improving their customer support and billing. These investments will be necessary for the successive accommodation of new services. Distinguishing different levels of service and consumer loyalty can be considered the main motivating factors for improvements and innovation in retail products and services.

3 LITERATURE REVIEW

Extensive work on retail electric power market analysis was done in three consecutive papers by Gabriel *et al* (2002, 2004, 2006). These focus specifically on the US retail electric power market and use stochastic optimization models and Monte Carlo simulation. The issues discussed are optimal price and quantity determination for retail contracts and settlement risk. Gabriel *et al* (2002) use Monte Carlo simulation to describe strategies for determining forward load positions and deciding which give the highest profit. Gabriel *et al* (2004) extended this work by computing optimal solutions from a mixed-integer linear program and making the outcome prescriptive: what the retailers ought to do to maximize profit in an uncertain market environment. Gabriel *et al* (2006) built on a more complex optimization problem for retailers, where contracts had to be set up with both producers and end-users under the conditions for profit maximization and a given level of settlement risk.

Hatami *et al* (2009) propose a model that uses mixed-integer stochastic programming to determine retailers' optimal selling prices and procurement policies (such as spot market, forward contracts, call options and own production) for a specific period. They use conditional value-at-risk (CVaR) methodology to model risk, and competition is determined by a market share function. Nazari and Akbari (2013) present an optimal strategy for a retailer, which involves both bilateral and power exchange contracts. Their optimization algorithm additionally determines the optimal amount of interruptible load and the selling price, and is solved through Monte Carlo simulation. Yusta *et al* (2005) develop an optimization problem to find the optimal selling prices for electric power to maximize the electricity suppliers' economic profit. The problem is then applied to several cases investigating the impact of tariff discounts, demand elasticity and price strategy on profit. Zugno *et al* (2013) also analyze retailers' optimal behavior but in the form of a Stackelberg game in which consumers are players as well. The authors model dynamic prices and show that this type of pricing scheme can be highly effective for achieving load shifting.

There are also numerous papers that study competition in electricity retail markets. Defeuilley (2009) accounts for two features that have to be present if the introduction of retail competition is to yield the expected positive effects. First, there should be a wide range of choices offered to customers. Second, there should be the necessary technology available that will allow for access from new entrants and developing radical innovations. Furthermore, Defeuilley points out that, with the opening up of retail competition, new opportunities will be created for active customers (those that are willing to change supplier or contract), but it is not clear whether retail competition will bring any gains for inactive customers. Littlechild (2009) provides counterarguments to Defeuilley's assertion that the introduction of electricity retail competition into power markets failed to produce the expected positive results. According to Littlechild, neither constraints on consumers' decision-making nor constraints on technology should be able to cast any doubt on the beneficial impacts from retail market competition. He also shows through specific examples that, when allowed, retail competition has in fact delivered more than initially expected. In an earlier work, Littlechild (2006) describes the status of competition and contracts in the Nordic residential electricity market, where he accounts for the increasing use of new products over time and for considerable product innovation. Also, he doubts the ability of regulative authorities to act as a substitute for retail competition. Annala and Viljainen (2009a,b) discuss the impact of retail electricity market models on competition and what specific changes might be required in the Nordic electricity retail market models in order to fit into a common Nordic end-user market for electricity. According to Annala and Viljainen, successive retail competition can be achieved through different market models and they discuss the features of various models, including the supplier-centric one. They consider the process of Nordic end-user market integration to provide an important experience for further integration on a European level.

This paper provides a novel approach through which retailers' strategies, increased competition and smart metering (via related service improvements) are simultaneously accounted for. We consider effective retail competition, active customers and smart metering to be the three pillars of the future Nordic end-user market.

As with many of the papers described above, our approach is based on developing an optimization model through which the expected profit for an electricity retailer is maximized. However, vital assumptions are made regarding the market model and smart-metering functionalities. We look into a two-retailer case where one retailer responds hourly with a certain price markup and service level to the other retailer's choices for equivalent decision variables.

4 NOTATION AND DEFINITIONS

The following notation is used in the mathematical model presented in Section 5.

- N: the set of possible realizations for the market base. The market base is defined as the total number of customers that are using or are likely to use the products and services offered by a retailer.
- n: realizations of N.
- $\tilde{x}_{in}$: stochastic market base for retailer i with mean $\bar{x}_i > 0$ and variance σ^2 that occurs with probability p_n. For modeling purposes we transform $\tilde{x}_{in}$ into a GWh measure.
- p_n: probability of the market base $\tilde{x}_{in}$ actually occurring, where $\sum_n p_n = 1$.
- Δ_i: price markup for real-time price contracts offered by retailer i; $\Delta_i = P_i - P_{\text{sm}}$, where P_i is the final tax-free price offered by the retailer and P_{sm} is the price in the spot market. Price markup in Norway is measured typically in øre/kWh, but we use the equivalent measure kNKr/GWh (thousand Norwegian Krones per GWh) for the ease of model simulations in this paper.
- s_i: investment in service for retailer i (kNKr). The higher the investment in service, the higher the service level is as a performance criterion for satisfying customers' needs. In this paper the terms "investment in service" and "service level" are used interchangeably.
- α: own-price demand sensitivity (GWh).

- β: cross-price demand sensitivity (GWh).
- η: demand sensitivity for the products and services of one retailer in response to own service level (GWh).
- μ: demand sensitivity for the products and services of one retailer in response to the other retailer's service level (GWh).
- ξ_i: service investment efficiency coefficient for retailer i, $\xi_i > 0$. The higher the value of ξ_i, the less efficient the investment is in cost terms.
- π_i: pure price markup profit for retailer i.
- $\tilde{\pi}_{in}$: net profit for retailer i when the market base is $\tilde{x}_{in}$.
- q_i: electricity demand satisfied by retailer i.
- τ: maximum allowed level of variance of the expected profit (kNKr).

Note that the temporal aspect, while important, as discussed above, has been deliberately suppressed in order to analyze several scenarios more easily. Thus, the model to be presented in the next section can be considered for a typical hour.

5 MATHEMATICAL MODEL

In this section we describe the mathematical problem faced by the retailer. It includes the objective function that is to be optimized and a risk constraint. The service level for each firm is quantified by the respective investment in service. Each retailer's demand is determined by the own price and service level and that of the competitor. We only consider the decisions taken by one of the two retailers (retailer i), while the values for the other retailer (retailer j) are held fixed.

5.1 Objective function

The objective function in this model is to maximize the retailer's expected profit. In constructing the objective function we follow the approach of Xiao and Yang (2008). The objective function consists of the following parts.

5.1.1 Profit from price markup

The profit is calculated as $\pi_i = \Delta_i q_i$, where q_i is electricity demand which, for a given realization of n, is given by

$$q_{in} = \tilde{x}_{in} - \alpha\Delta_i + \beta\Delta_j + \eta s_i - \mu s_j. \tag{5.1}$$

In the demand function (5.1), demand for electricity depends on the market base and will decrease with the increase in own price markup Δ_i and other retailer's service level s_j (negative coefficients on Δ_i and s_j). Additionally, demand increases own service level s_i or increases when the other retailer increases its price Δ_j (positive coefficients on s_i and Δ_j).

5.1.2 Investment costs

We choose a cost function of the following functional form:

$$c_i(s_i) = c_i = \xi_i s_i^2, \quad \xi_i > 0. \tag{5.2}$$

The cost function is posited as a quadratic function of the service level s_i to allow for varying marginal levels of cost that change in accordance with the service level. Combining (5.1) and (5.2), the profit for the retailer i is equivalent to

$$\tilde{\pi}_{in} = \Delta_i q_{in}(\tilde{x}_{in}) - c_i, \tag{5.3}$$

$$\mathbb{E}(\tilde{\pi}_{in}) = \Delta_i(\bar{x}_i - \alpha\Delta_i + \beta\Delta_j + \eta s_i - \mu s_j) - \xi_i s_i^2, \tag{5.4}$$

where $\bar{x}_i = \mathbb{E}(\tilde{x}_{in})$ over n.

It is important to note that investments in service (s_i, s_j) are considered as a proxy for the quality of the service, which, as previously described, can taken many forms. This is reasonable since larger investments in the retailer's own service should, all things being equal, increase their electricity demand (see (5.1)). Likewise, more investments in service by the other retailer should lessen the demand.

5.2 Constraint

Retailers have different risk preferences and these are modeled through incorporating the variance of the expected profit into the optimization problem.[4] Retailers require that the variance of the expected profit is less than or equal to a certain value. The higher the value of τ, the less risk averse the retailer is:

$$\mathrm{var}(\tilde{\pi}_{in}) \leqslant \tau. \tag{5.5}$$

[4] Using the variance of the expected profit is just one example of how the retailer's risk preferences can be captured. However, there exist a number of other ways to model the risk attitude of an electricity retailer (eg, through chance constraints, semivariance and risk measures such as VaR and CVaR). Unlike the variance approach, which penalizes both upward and downward deviations from the expected value, the semivariance measures only the variability of returns that are below the mean value (Huang 2008). The choice of a specific risk modeling approach depends on the extent to which risk needs to be incorporated in the model. We consider the variance to be a suitable measure of risk preferences in our model.

Many other choices for modeling risk could also be made in the constraints or the objective. Some examples include: semivariance, which only evaluates the downside risk; shortfall, which measures the probability of insufficient profit (or other measures); CVaR, which concentrates on the expected profit for the worst scenarios that could be realized (Huang 2008; Conejo *et al* 2010). Alternatively, a relative risk measure, divided by some key quantity, could also be considered but has not been. All these measures have different assumptions about what part of risk is to be minimized or controlled, and of course would affect not only the profit but also the level of service to the customers. Also, for simplicity we have only considered profit risk, but we could easily incorporate other types, such as varying market share.

5.3 Complete problem

Combining the objective function and constraints in (5.4) and (5.5), we end up with the following risk-constrained optimization problem:

$$\max_{\Delta_i, s_i} \Delta_i(\bar{x}_i - \alpha\Delta_i + \beta\Delta_j + \eta s_i - \mu s_j) - \xi_i s_i^2$$
$$\text{such that } \operatorname{var}(\tilde{\pi}_{in}) \leqslant \tau,\ \Delta_i \geqslant 0,\ s_i \geqslant 0, \quad (5.6)$$

which is equivalent to

$$\max_{\Delta_i, s_i} \Delta_i\bar{x}_i - \alpha\Delta_i^2 + \beta\Delta_i\Delta_j + \eta\Delta_i s_i - \mu\Delta_i s_j - \xi_i s_i^2$$
$$\text{such that } \operatorname{var}(\tilde{\pi}_{in}) = \sum_n [\Delta_i(\tilde{x}_{in} - \bar{x}_i)]^2 p_n \leqslant \tau,\ \Delta_i \geqslant 0,\ s_i \geqslant 0. \quad (5.7)$$

5.4 The Karush–Kuhn–Tucker conditions

We present here the conditions for sufficiency of the Karush–Kuhn–Tucker (KKT) conditions. A detailed description of the mathematical procedures is provided in Appendix A.

As we show in Appendix A, the less than or equal to constraint in (5.7) is convex, and the only additional condition for sufficiency of the KKT conditions is convexity of the objective function as long as

$$4\alpha\xi_i - \eta^2 \geqslant 0. \quad (5.8)$$

6 DATA

In this section we present the data used in the model simulations. The model simulations involve a two-retailer case. The price and service values for retailer 1 (modeled as retailer i in Section 5) are endogenous, and those for retailer 2 (modeled as retailer j in Section 5) are exogenous and will be provided in this section.

TABLE 1 Demand base and probabilities for electricity retailers operating in Norway, as used in the model.

Demand (GWh)	Probability
2	0.01
10	0.06
20	0.08
40	0.08
60	0.08
80	0.12
200	0.28
400	0.12
800	0.06
1000	0.04
2000	0.03
4000	0.02
6000	0.01
8000	0.01

6.1 Demand

Using the Norwegian Water Resources and Energy Directorate's data on number of customers per retailer in Norway (Pettersen 2012), the market base in GWh per year is calculated as follows:

$$\tilde{x}_{in}(\text{GWh/year}) = (1.12K)0.02. \tag{6.1}$$

In (6.1) the market base (GWh/year) for a retailer equals the upper average amount of electricity demanded by customers; it is based on the current number of customers per retailer in Norway (K), and these numbers are adjusted for the possibility for increase in demand, with 12% due to supplier switching.[5] Also, we assume a usage volume of 20 000 kWh/year (0.02 GWh/year) per customer metering point.[6] This is the upper average value for electricity consumption in Norway. Although the use of measures in øre and kWh is more common for the end-user market, the equivalent

[5] According to a market report for the last few years, 11.2% of the Norwegian customers switched electricity supplier in 2011 (Nordic Energy Regulators 2012). We use a 12% factor to account for the increasing trend in supplier switches over the years.

[6] Norway has the second highest electricity power consumption per capita in the world. According to the World Bank database for 2009–13 the value for Norway is 23 147 kWh/year versus, for example, 5472 kWh/year for the United Kingdom (see http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC). The assumption of 20 000 kWh is based on the actual electricity consumption in Norway during the past year and we consider it appropriate.

in numerical value measures of kNKr and GWh are preferred in the calculations for consistency. With the requirement for the model to be run for an hourly resolution, the average hourly demand is calculated based on (6.1). Note that the model represents a typical hour but does not actually have a time index. The probabilities p_n for $\tilde{x}_{in}$ presented in Table 1 on the preceding page are calculated based on the frequencies of the normalized values for electricity demand per retailer.

6.2 Demand sensitivity

A starting value for the calculation of demand sensitivity to own-price changes is taken from the work of Halvorsen and Larsen (2001). They estimate the price elasticity of electricity demand for the Norwegian households to be −0.4. This is the short-run Cournot elasticity for the whole period 1976–93. Taking this value as a starting point, we assume a cross-price elasticity of 0.3. The elasticity of demand to other retailers' prices is expected to be lower due to switching costs. To be consistent in our expectations for demand sensitivity, we choose the value of demand elasticity to own service level to be 0.6 and that to other retailers' service to be −0.5. We find these values to be appropriate, as they indicate a higher elasticity to service rather than price, which we expect to be the case in a common Nordic power market. In addition, the elasticities to own prices and service are higher than the cross elasticities: a fact that can be justified by switching cost and consumers' loyalty to currently supplying retailers.

Based on the above elasticity measures we find the demand sensitivity values for α, β, η and μ. In our calculations we use the yearly demand with highest frequency among electricity retailers that is available in the data: 100 GWh/year. For this yearly demand value, we calculate the average hourly decrease or increase in correspondence to the measures for own-price and cross-price elasticities. As a result we end up with the following values (in GWh):

$$\alpha = 0.0046, \qquad \beta = 0.0034, \qquad \eta = 0.0067, \qquad \mu = 0.0058.$$

6.3 Service investment cost efficiency coefficient

When deciding on the service investment cost efficiency coefficient we should always check if the chosen value satisfies the condition in (5.8), to ensure convexity of the objective function. For the given values for α and η, the value of ξ_i should be greater than 0.00256. We choose a value of $\xi_i = 0.01$ for our model simulations to make sure the objective function is convex.

6.4 Values for Δ_2 and s_2

The nominal value chosen for the price markup for retailer 2, Δ_2 is 2.6 øre/kWh, or 26 000 NKr/GWh. This is the average electricity retail price markup for spot-price

TABLE 2 Optimal price markup and service investment for retailer 1.

ξ_i	Δ_2	s_2	τ	Δ_1	s_1	$\mathbb{E}(\tilde{\pi}_1)$
0.01	26	1	2	10.4	3.7	1.1

contracts and usage of 20 000 kW/h annually according to a market report for the second quarter of 2012 (Pettersen 2012). When it comes to the service investment made by retailer 2 (s_2) we take 1 (or 1000 NKr/h) as a starting point. Later we will vary this value and see how the increase in service investment (higher service level) will affect retailer 1's price, service investment and profit and do the same for Δ_2 as well.

6.5 Variance of the expected profit

The maximum allowed variance differs in the separate model simulations, reflecting the retailer's risk preferences. The minimum value we use in the model is 1000 NKr/h, and the maximum reaches 5000 NKr/h.

7 NUMERICAL RESULTS AND DISCUSSION

7.1 Results

Our results reflect several model simulations, using the GAMS software for optimization, where the impact from changes in various parameters is examined. We start by finding the optimal values for price and service level for retailer 1, given some predefined values for retailer 2. Input data and results are given in Table 2.

Under the given assumptions for price markup (Δ_2) and service investment (s_2) for retailer 2, retailer 1 chooses to offer a lower price markup of 1.04 øre/kWh (10.4 kNKr/GWh) but a higher service level, of 3.7. These results rest on a number of conditions and should be viewed with caution. Our aim is to present the trends and dependencies in the electricity retail market, rather than come up with specific values. These initial results confirm our hypothesis that, in a common Nordic power market, service level will be an important contributor to a retailer's profit. This is, however, valid under the assumed values for demand sensitivity to service.

As a next step, model simulations are run: one where the price markup for retailer 2 constantly decreases, and two more where the values entered for retailer 2's price

TABLE 3 Results from model simulations. [Table continues on next four pages.]

(a) Model simulation 1
(decreasing the price markup for retailer 2)

Iteration	$\boldsymbol{\Delta_2}$	$\boldsymbol{\Delta_1}$	s_1	$\mathbb{E}(\tilde{\pi}_1)$
B	40.00	17.14	5.83	2.18
1	38.00	17.14	5.83	2.07
2	36.10	17.14	5.83	1.96
3	34.30	17.14	5.83	1.85
4	32.58	17.14	5.83	1.75
5	30.95	17.14	5.83	1.66
6	29.40	17.14	5.83	1.57
7	27.93	17.14	5.83	1.48
8	26.54	17.14	5.83	1.40
9	25.21	17.14	5.83	1.32
10	23.95	17.14	5.83	1.25
11	22.75	17.14	5.83	1.18
12	21.61	17.14	5.83	1.11
13	20.53	17.14	5.83	1.05
14	19.51	16.95	5.76	0.99
15	18.53	16.47	5.60	0.93
16	17.61	16.01	5.44	0.88
17	16.72	15.57	5.30	0.84
18	15.89	15.16	5.16	0.79
19	15.09	14.77	5.02	0.75
20	14.34	14.40	4.90	0.71

markup (Δ_2) and service (s_2), respectively, increase. Retailer 1's risk preferences are given by $\tau = 5$ (risk-loving). First, Δ_2 is decreased by 5% and then increased by 5% for every iteration. Starting values are 4 and 1 øre/kWh, respectively. And in the third simulation s_2 is increased by 0.5 (500 NKr/h investment value) for every iteration, starting from 1 (1000 NKr/h). These initial values can be seen in the base row (B) in Table 3. The fourth model simulation represents a simultaneous increase in Δ_2 and s_2.

In a fifth model simulation, the retailer's sensitivity to risk τ is varied. The values for the variance of the expected profit τ increase by 10% for each subsequent iteration (1–20), having 1 as a starting value. The input data for ξ_i, Δ_2, s_2 are shown in Table 2 on the preceding page. We find that decreasing retailers' sensitivity to risk (ie, increasing the value of τ) results in not only higher profit but also higher investment in service and higher price markup.

TABLE 3 Continued.

(b) Model simulation 2
(increasing the price markup for retailer 2)

Iteration	Δ_2	Δ_1	s_1	$\mathbb{E}(\tilde{\pi}_1)$
B	10.00	12.25	4.17	0.52
1	10.50	12.50	4.25	0.54
2	11.03	12.76	4.34	0.56
3	11.58	13.03	4.43	0.59
4	12.16	13.32	4.53	0.61
5	12.76	13.62	4.63	0.64
6	13.40	13.93	4.74	0.67
7	14.07	14.26	4.85	0.70
8	14.77	14.61	4.97	0.74
9	15.51	14.98	5.09	0.77
10	16.29	15.36	5.22	0.81
11	17.10	15.76	5.36	0.86
12	17.96	16.18	5.50	0.90
13	18.86	16.63	5.65	0.95
14	19.80	17.09	5.81	1.01
15	20.79	17.14	5.83	1.06
16	21.83	17.14	5.83	1.12
17	22.92	17.14	5.83	1.19
18	24.07	17.14	5.83	1.26
19	25.27	17.14	5.83	1.33
20	26.53	17.14	5.83	1.40

It is important to notice that all results represent hourly values for a typical hour. Here we have made assumptions that smart-metering technologies enable hourly measuring and pricing. Numerical results are provided in Table 3 on the facing page.

7.2 Discussion

Model simulation 1

We start the discussion focusing on the possibility for some further decrease of a retailer's price markup. Although we have pointed out that retail margins are currently small, there is still an option for some retailers to decrease their price markup. An average retail markup of 4 øre/kWh ($\Delta_2 = 40$) is chosen as a starting value in the simulation.

TABLE 3 Continued.

(c) Model simulation 3 (increasing the service level for retailer 2)				
Iteration	s_2	Δ_1	s_1	$\mathbb{E}(\tilde{\pi}_1)$
B	1.00	17.14	5.83	1.37
1	1.50	17.14	5.83	1.32
2	2.00	17.14	5.83	1.27
3	2.50	17.14	5.83	1.22
4	3.00	17.14	5.83	1.17
5	3.50	17.14	5.83	1.12
6	4.00	17.14	5.83	1.07
7	4.50	17.14	5.83	1.03
8	5.00	16.84	5.73	0.98
9	5.50	16.43	5.59	0.93
10	6.00	16.01	5.45	0.88
11	6.50	15.60	5.30	0.84
12	7.00	15.19	5.16	0.79
13	7.50	14.77	5.02	0.75
14	8.00	14.36	4.88	0.71
15	8.50	13.95	4.74	0.67
16	9.00	13.53	4.60	0.63
17	9.50	13.12	4.46	0.59
18	10.00	12.70	4.32	0.56
19	10.50	12.29	4.18	0.52
20	11.00	11.88	4.04	0.49

It can be seen in Figure 2 on page 37 that retailer 1 keeps the price markup lower than that of retailer 2 until the last iteration, when retailer 1 offers a retail margin of 1.44 øre, compared with 1.43 øre for retailer 2. Retailer 1 will not need to keep offering a lower price, as customers are in general insensitive to such small differences at low price markup levels.

Also, when retailer 2 decreases its price markup, Δ_2, the expected profit $\mathbb{E}(\tilde{\pi}_1)$ of retailer 1 steadily decreases, while retailer 1's service level remains constant at 5.83, before starting to drop from the fourteenth iteration, reaching a final value of 4.9 (Table 3 on page 32, model simulation 1). The decrease in retailer 1's profit is indicative of customers' preferences for price and service under the sensitivity assumptions made: customers will prefer the lower price for the given service level. Retailer 1's choices for service level show a trend for maintaining a higher service

TABLE 3 Continued.

(d) Model simulation 4 (increasing both the price markup and the service level for retailer 2)

Iteration	Δ_2	s_2	Δ_1	s_1	$\mathbb{E}(\tilde{\pi}_1)$
B	10.00	1.00	12.25	4.17	0.52
1	10.50	1.50	12.09	4.11	0.50
2	11.03	2.00	11.93	4.06	0.49
3	11.58	2.50	11.79	4.01	0.48
4	12.16	3.00	11.66	3.97	0.47
5	12.76	3.50	11.55	3.93	0.46
6	13.40	4.00	11.45	3.89	0.45
7	14.07	4.50	11.37	3.87	0.45
8	14.77	5.00	11.30	3.84	0.44
9	15.51	5.50	11.25	3.83	0.44
10	16.29	6.00	11.22	3.82	0.43
11	17.10	6.50	11.21	3.81	0.43
12	17.96	7.00	11.22	3.81	0.43
13	18.86	7.50	11.25	3.82	0.44
14	19.80	8.00	11.30	3.84	0.44
15	20.79	8.50	11.37	3.87	0.45
16	21.83	9.00	11.47	3.90	0.45
17	22.92	9.50	11.60	3.94	0.46
18	24.07	10.00	11.75	4.00	0.48
19	25.27	10.50	11.93	4.06	0.49
20	26.53	11.00	12.14	4.13	0.51

level up to a point where its price markup stays constant. But when the price markup starts to become lower, service level also decreases due to lower profit, and thus fewer service investment opportunities. At the same time it then becomes harder to compete with retailer 2's lowered prices.

Model simulation 2

If retailer 2's price markup happens to increase, retailer 1 can enjoy higher profits (Figure 3 on page 37). Retailer 1 may choose to offer a higher price markup when the electricity retail prices are low and when the difference in prices is not sufficient to motivate customers to change supplier. At the same time retailer 1 will aim at lower prices when the overall level of price markup becomes higher (Figure 4 on page 38). The ninth iteration is the crossing point for the two retailers' price markup

TABLE 3 Continued.

(e) Model simulation 5
(relaxing the risk constraint)

Iteration	τ	Δ_1	s_1	$\mathbb{E}(\tilde{\pi}_1)$
B	1.00	7.66	2.61	0.86
1	1.10	8.04	2.73	0.89
2	1.21	8.43	2.87	0.93
3	1.33	8.84	3.01	0.96
4	1.46	9.27	3.15	0.99
5	1.61	9.73	3.31	1.02
6	1.77	10.20	3.47	1.06
7	1.95	10.70	3.64	1.09
8	2.14	11.22	3.82	1.12
9	2.36	11.77	4.00	1.16
10	2.59	12.34	4.20	1.19
11	2.85	12.95	4.40	1.22
12	3.14	13.58	4.62	1.25
13	3.45	14.24	4.84	1.28
14	3.80	14.94	5.08	1.31
15	4.18	15.67	5.33	1.33
16	4.59	16.43	5.59	1.35
17	5.05	17.23	5.86	1.37
18	5.56	18.07	6.15	1.38
19	6.12	18.95	6.44	1.39
20	6.73	19.88	6.76	1.40

lines. Also, in Table 3 on page 32 it can be seen that both price markup and service stay constant from some point on (iteration 14, where $\Delta_1 = 1.7$ and $s_1 = 5.8$). Having reached these values, it is no longer profitable for the retailer to invest more in service or to change the price markup. This can be attributed to retailer 1's level of risk aversion: retailers do not like to increase prices further if they face the risk of losing customers.

Model simulation 3

In this model simulation we consider an increase in retailer 2's service level. Results indicate a smooth drop in the hourly profit (Figure 5 on page 38). We might expect that the more retailer 2 invests in service, the greater the chance that part of retailer 1's customers switch. Retailer 1 may try to decrease its price markup at some point (when

FIGURE 2 The impact of a decrease in retailer 2's price markup on retailer 1's price markup.

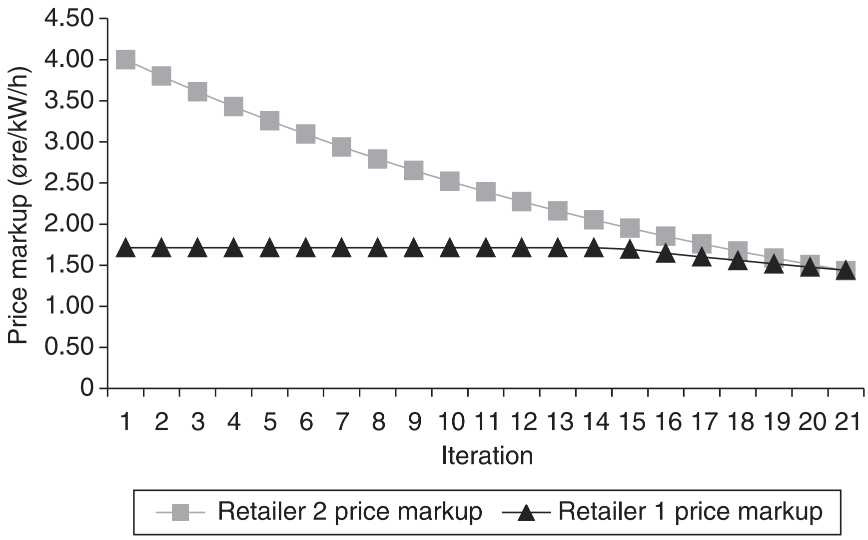
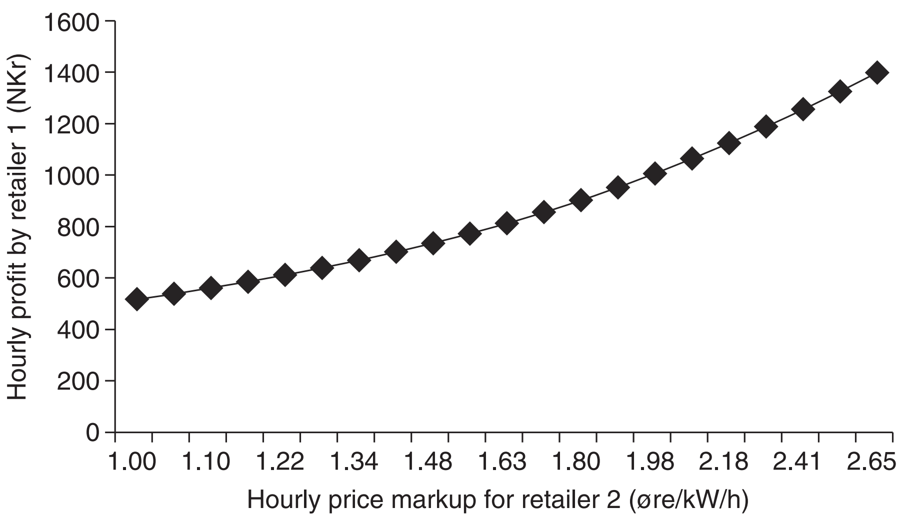


FIGURE 3 The impact of an increase in retailer 2's price markup on retailer 1's profit.



retailer 2 reaches a service level of 5 (Figure 6 on page 39)) in order to keep customers. At the same time, the continuous decrease in profit will cause a decrease in retailer 1's investment in service, which also starts dropping after retailer 2 reaches a service level of 4.5 (Figure 7 on page 39).

FIGURE 4 Comparison of price markup for the two retailers under a constant increase in retailer 2's price markup.

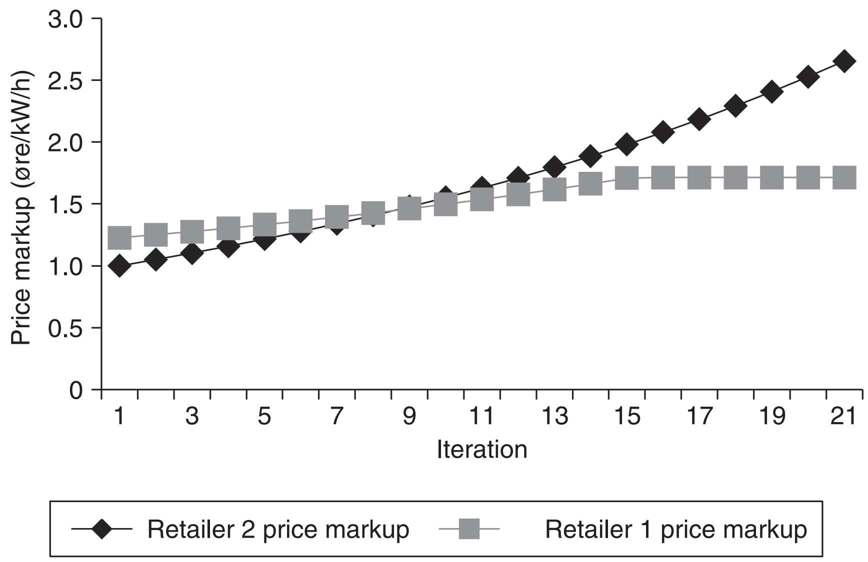
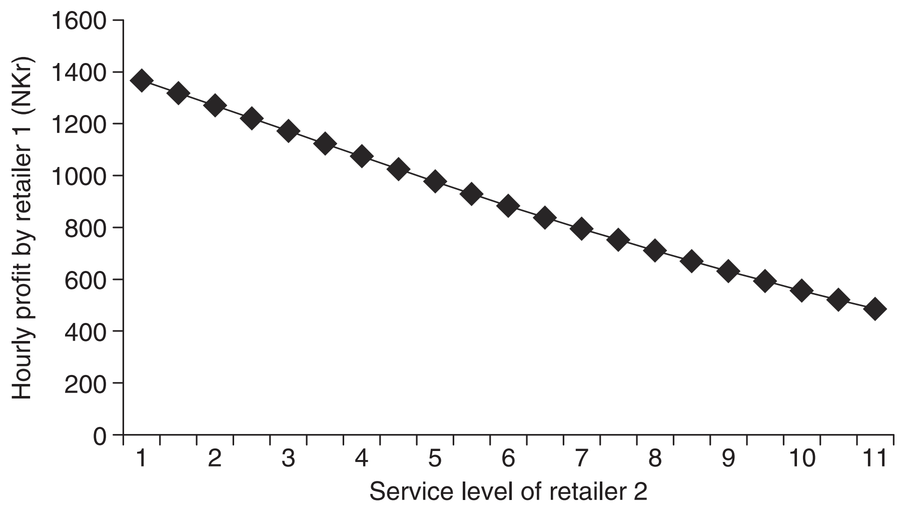


FIGURE 5 The impact of an increase in retailer 2's service level on retailer 1's profit.



Model simulation 4

Here we choose to observe the effect of a simultaneous increase in the price markup and service level of retailer 2: a combination of our second and third simulations. This is a highly probable development, as retailers who offer a variety of innovative

FIGURE 6 The impact of an increase in retailer 2's service level on retailer 1's price markup.

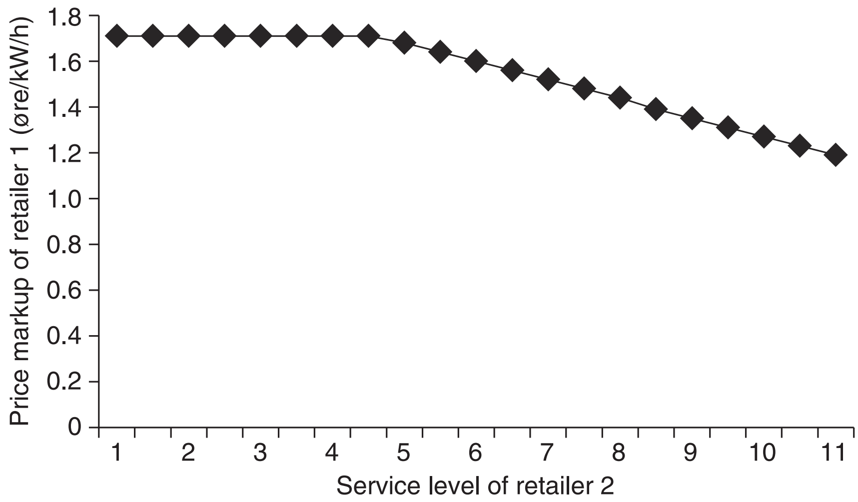
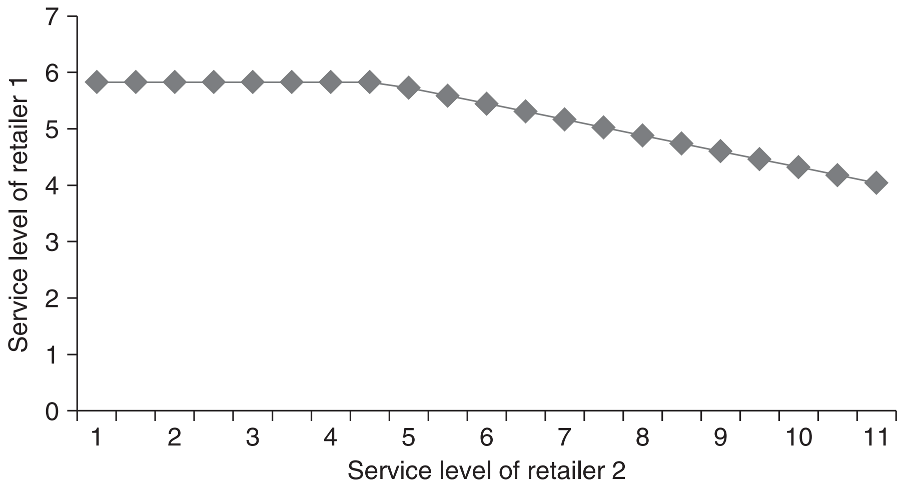
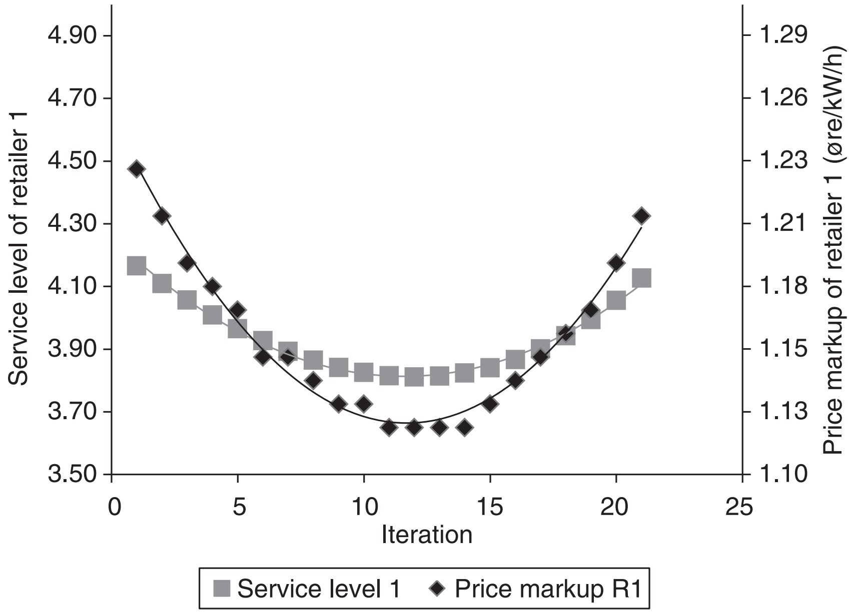


FIGURE 7 The impact of an increase in retailer 2's service level on retailer 1's service level.



services can be attractive to customers despite the higher prices they offer. Price markup increases by 5% in every iteration, while service level increases by 0.5. The rest of the model's parameters are kept as in the first and second model simulations. A simultaneous increase in the two independent variables results in two convex curves for retailer 1's price and service (Figure 8 on the next page).

FIGURE 8 Effects of a simultaneous increase in retailer 2's price markup and service level on retailer 1's price markup and service level over the course of twenty iterations.



Black line: $y = 0.001x^2 - 0.0225x + 1.2533$. Gray line: $y = 0.0033x^2 - 0.0767x + 4.257$.

FIGURE 9 Effects of a simultaneous increase in retailer 2's price markup and service level on retailer 1's price markup and profit over the course of twenty iterations.

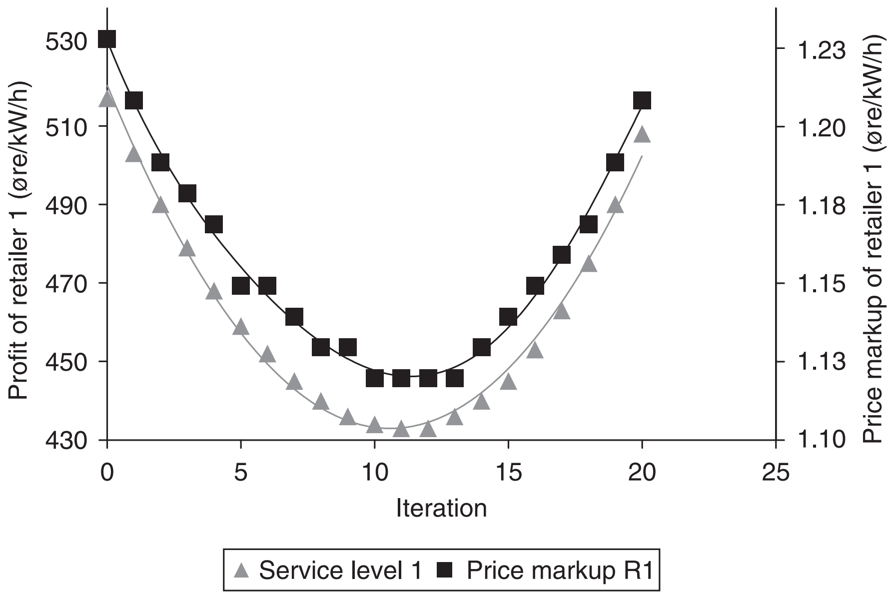
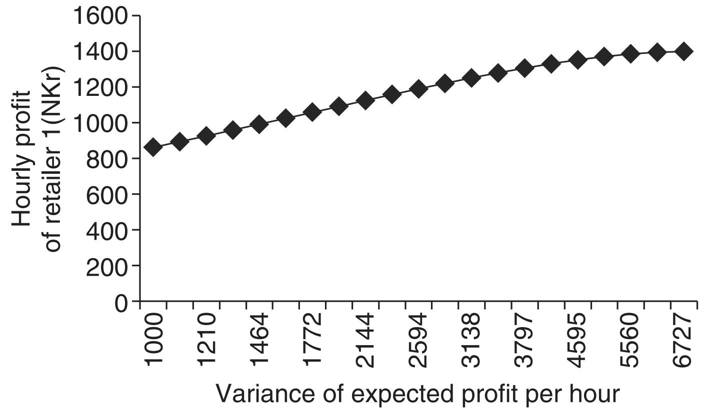


FIGURE 10 The impact of risk constraint relaxation on retailer 1's profit.



Also, from Figure 8 on the facing page, it can be concluded that retailer 1's price and service response will start to decrease, followed by an increase after the twelfth iteration. As retailer 2 increases its price and service, retailer 1's strategy will be to decrease prices in order to attract customers. However, a lower price markup will result in lower profit. As can be seen in Figure 9 on the facing page, retailer 1's price markup and profit initially decrease and then increase simultaneously.

With the further increase in retailer 2's price markup and service after iteration 12, retailer 1 chooses to offer higher prices. However, the prices offered by retailer 1 are still lower than those of retailer 2. At the same time, retailer 1 has to increase service investments, as the increase in retailer 2's service level makes the purely lower-pricing strategy of retailer 1 insufficient for making profit and maintaining demand base. The shape of the line for equilibrium solutions for profit resembles those for price markup and service level.

Model simulation 5

The results from the fifth model simulation show that allowing the variance τ of the expected profit for retailer 1 to increase (relaxing the risk constraint) will lead to increasing profit. This increase will be diminishing: the percentage increase in hourly profit declines under a constant percentage increase in the variance value (Figure 10). With the increase in the values for maximum allowed variance τ, retailer 1's price markup and service level increase as well (Figure 11 on the next page and Figure 12 on the next page). Risk-loving retailers will be prone to offer higher prices and invest more in service. A risk-loving retailer may expect that customers are passive and will not switch to other retailers despite the higher prices, or that the higher service level

FIGURE 11 The impact of risk constraint relaxation on retailer 1's price markup.

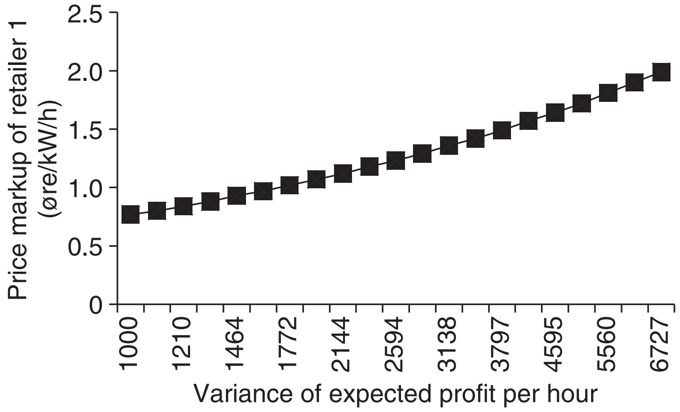


FIGURE 12 The impact of risk constraint relaxation on retailer 1's service.

will attract new customers and keep old ones and thus neutralize the effect of the higher price markup faced by customers.

8 CONCLUSIONS

In recent years technological development has made possible hourly measurement of electricity usage and provided the tools for building smart metering through which resources can be used in an optimal way. With varying amounts of household electricity consumption throughout the day, and variations in the marginal costs for producing electricity, the smart-metering concept presents a good solution to decreasing peak load, securing system stability and preventing grid inefficiencies. However, optimal operation of smart metering is difficult to achieve without proper economic incentives. Electricity retailers are best placed to provide these incentives.

In this paper we focus on the competition between electricity retailers in a common Nordic power market. An integrated market that combines the electricity end-user markets of Norway, Sweden, Denmark and Finland will put pressure on retailers in each country to compete. To survive in this larger market, electricity retailers will have to reconsider their price and service strategies. But, while the current retail price margins are small and leave a very limited scope for further price reductions, services can be considered a vital tool for successive differentiation from other competitors. Innovative services that capture the benefits from smart metering are probably the best option for retailers who want to stay competitive, keep their existing customers and be attractive for new ones.

By representing market competition in Norway through a simplified two-retailer model we see that when one of the competing retailers (retailer 2) decreases its price markup, the other (retailer 1) will experience decreasing profit and will respond by keeping its own price markup lower until it reaches levels of below 1.5 øre. From then on, retailer 1 will offer a price markup that is slightly higher than that of retailer 2. At that point, the overall price markup level is so low that small differences will not be decisive for consumers. But when retailer 2 increases its price markup the response by retailer 1 is to offer a higher price markup at low price markup levels and a lower price markup at higher price markup levels. Retailer 1's price markup will increase until it judges there is a higher risk of losing customers.

When one of the retailers increases its service level, it will attract some of the competing retailer's clients and thus increase its number of customers. The competing retailer will then respond by decreasing price markup to attempt to retain its demand base. However, under a continuous increase in one retailer's service, the profit of the other will decrease, and so will its price markup offers and investments in service. These results give us an idea of how severe retail market competition can be, in particular, when some retailers innovate and others do not. Although limited to a two-retailer case, the results from the model simulations are indicative for a retail market where a higher number of participants are present. In a large common Nordic power market with intensive competition and customers connected through smart-metering technologies, retailers who do not offer sufficient service may lose their market positions.

If both the price markup and service level of one retailer continuously increase, the competing retailer's price, service level and profit will initially decline, before rising again. The rise is caused by the dominating increase in the first retailer's price markup and the second retailer's strategy to compete in service to try to keep its customers. The combined effect of price and service decisions made by the two retailers on profit will be a stringent determinant to the retailers' market strategies.

Finally, we show that the more risk averse a retailer is, the higher its price markup, service level and expected profit. Less risk-averse retailers will make higher investments in service and, under the given assumptions for demand sensitivity, will also offer slightly higher prices. We therefore expect that it will be innovative services rather than small price differences that make a retailer attractive to customers. Retailers that risk investing in new products and services that capture the needs of their clients in a highly competitive electricity market, dominated by smart-metering technology, could make higher profits.

The expected profit values per hour given in this paper are very small, because they represent the expected price-markup-made profit minus the investment in service and do not account for the profit associated with various new retail services which will become common. The profit from new services is hard to estimate as we do not know exactly what they are or how these will operate. But what we can expect is that there will be a wide range of services to answer various needs of different types of customers. Electricity retailers who manage to capture these needs and answer them using the functionalities offered by smart-metering technologies should anticipate a profitable future in a common Nordic end-user power market.

APPENDIX A

In this appendix we investigate the objective function and constraint set for convexity that will make the KKT conditions sufficient for optimality of a solution to the constrained nonlinear program (5.7).

The retailer's maximization problem is

$$\max_{\Delta_i, s_i} \Delta_i \bar{x}_i - \alpha\Delta_i^2 + \beta\Delta_i\Delta_j + \eta\Delta_i s_i - \mu\Delta_i s_j - \xi_i s_i^2$$
$$\text{such that } \operatorname{var}(\tilde{\pi}_{in}) = \sum_n [\Delta_i(\tilde{x}_{in} - \bar{x}_i)]^2 p_n \leqslant \tau, \ \Delta_i \geqslant 0, \ s_i \geqslant 0. \quad \text{(A.1)}$$

The objective function of (A.1) transformed into an equivalent minimization problem is

$$f(\Delta_i, s_i) = -\Delta_i\bar{x}_i + \alpha\Delta_i^2 - \beta\Delta_i\Delta_j - \eta\Delta_i s_i + \mu\Delta_i s_j + \xi_i s_i^2, \quad \text{(A.2)}$$

with the corresponding Hessian matrix

$$\nabla^2 f(\Delta_i, s_i) = H_i = \begin{bmatrix} \dfrac{\partial^2 f}{\partial\Delta_i^2} & \dfrac{\partial f}{\partial\Delta_i\,\partial s_i} \\ \dfrac{\partial^2 f}{\partial s_i\,\partial\Delta_i} & \dfrac{\partial^2 f}{\partial s_i^2} \end{bmatrix} = \begin{bmatrix} 2\alpha & -\eta \\ -\eta & 2\xi_i \end{bmatrix}. \quad \text{(A.3)}$$

The function $f(\Delta_i, s_i)$ is convex in Δ_i and s_i if and only if H_i is positive semidefinite (Bazaraa *et al* 2006).

Given that α and ξ_i are assumed to be nonnegative, so that the principal minors $\det[(H_i)_{(1,1,)}] \geqslant 0$ and $\det[(H_i)_{(2,2)}] \geqslant 0$, the condition for positive semidefiniteness is the following:

$$\det(H_i) = 4\alpha\xi_i - \eta^2 \geqslant 0. \tag{A.4}$$

When (A.4) holds, the objective function in (A.1) is convex. For the risk constraint the positivity of p_n and the squared term prove convexity. Thus, the KKT conditions are sufficient for optimality of the less than or equal to constraint in (A.1). For completeness, we now give the KKT conditions for the optimization problem (A.1):

$$\begin{gathered}
\begin{pmatrix} -\bar{x}_i + 2\alpha\Delta_i - \beta\Delta_j - \eta s_i + \mu s_j \\ -\eta\Delta_i + 2\xi_i s_i \end{pmatrix} \\
+\lambda_1 \begin{pmatrix} 2\Delta_i \sum_n (\tilde{x}_{in} - \bar{x}_i)^2 p_n \\ 0 \end{pmatrix} + \lambda_2 \begin{pmatrix} -1 \\ 0 \end{pmatrix} + \lambda_3 \begin{pmatrix} 0 \\ -1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \\
\sum_n [\Delta_i(\tilde{x}_{in} - \bar{x}_i)]^2 p_n - \tau \leqslant 0, \\
\lambda_1 \geqslant 0, \quad \lambda_1\Big[\sum_n (\Delta_i(\tilde{x}_{in} - \bar{x}_i))^2 p_n - \tau\Big] = 0, \\
-\Delta_i \leqslant 0, \quad \lambda_2 \geqslant 0, \quad \lambda_2(-\Delta_i) = 0, \\
-s_i \leqslant 0, \quad \lambda_3 \geqslant 0, \quad \lambda_3(-s_i) = 0.
\end{gathered}$$

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Paper III

The impact of end-user market integration and smart grid on electricity retailers in the Nordic region

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ABSTRACT

The Nordic end-user market for electricity is subject to significant changes. The energy authorities within the Nordic countries are intensively working to create a common electricity retail market and expect it to be fully operational in 2018, and all customers should have installed smart meters by 2019. These changes are of particular concern for the suppliers of retail electric power as competition will increase and the retail products and offers related to the smart grid and the specific customers' needs will gain importance. With the help of a mixed complementarity problem formulation that describes a simplified market setting with two competing retailers, we analyze the impact of the pending market changes on electricity retailers' price markup and profit.

KEYWORDS

Market integration; Electricity retail competition; Smart grid; Mixed complementarity problem;

1. INTRODUCTION

The Nordic end-user electricity market is undergoing changes and since 2008, the Nordic Energy Regulators (NordREG) have been working on the establishment of a common Nordic end-user market. The common market design will rely on harmonization in the electricity retail sectors of Norway, Sweden, Finland and Denmark[1] and is expected to intensify competition in both price and service [1]. Within a common Nordic end-user market the consumers will be able to choose their electricity supplier[2] freely and independently of its country of origin and this fact could provoke changes to electricity retailers' strategies. For power retailers, it will be more important than ever to closely monitor other retailers, making decisions after considering rival firms' pricing and service strategies.

The Nordic electricity market is suitable for further market integration in the form of a common retail market. As noted by Joskow [2] the Nordic countries, together with Texas and the UK have policy frameworks that are likely to be most successful in stimulating trade in electricity retail products and the development of a viable electricity retail sector. Within this sector the price and service strategies of the retailers should be considered their most powerful competition tool. Issues related to the increasing importance of service offers that correspond to a wide in scope technology innovation in the energy sector and their link to the retailers' price markup decision and profit have been discussed [1]. The current work is a continuation of [1] and the nonlinear program used by Ilieva and Gabriel [1] has been transformed into a mixed complementarity problem (MCP) that is used to analyze the retailers' simultaneous decisions from a game-theoretic perspective. This paper goes beyond Ilieva and Gabriel [1] in several important ways: a new method for quantifying service is applied; the equilibrium solution's price markup for an average-sized retailer with high service level is defined; the market outcomes for retailers of different size are compared; the possible profit versus demand and price markup development with respect to the changing market environment (increased number of competitors, increased service level, increased consumer knowledge and increased demand flexibility) is discussed. While the modeling approach applied by Ilieva and Gabriel [1] has been extended to a game theory model that is better suited to reflect the strategies of competing retailers, part of the data used in the previous paper is kept for the new model simulations and for comparison purposes.

As noted by [3] and [4] within the game-theoretical framework complementarity models that represent the simultaneous optimization problems of interacting energy market participants have become increasingly important. In the literature, complementarity-based power market models have been used to represent the constrained optimization problems of various electricity market actors. Some of the scientific works, similar to [4], have focused on the producers' optimal strategies: [5], [6], [7], [8], [9], [10], [11]. In other papers the optimization

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[1] Iceland has been excluded from the term "Nordic retail market". There are no transmission cables to connect Iceland to the rest of the Nordic countries and Iceland is not participating in the Nordic electricity spot market.

[2] We use the terms supplier and retailer interchangeably.

problems of several groups of market players have been included in a single power market model. Hobbs and Helman [12] bring together the optimization problems of electricity producers, consumers and distributors and the market clearing conditions, while Ralph and Smeers [13] model simultaneously the behavior of generators and retail consumers. In [14] the focus is on power retailers and similar to this study, the response to retail prices and competition among rival suppliers is considered explicitly. However, in [14] a bilevel stochastic programming approach is applied. The usage of complementarity models for the electricity retail part of the energy sector has been limited. To our knowledge none of the so far published scientific articles in the electricity market field has represented the electricity retailers' behavior as a complementarity model. One reason for that could be the insufficient level of deregulation in the power sectors of many countries. Although during the last decade, a number of states in the U.S., Europe and Australia have implemented electricity retail programs, in many other parts of the world the electricity retail sector is still not deregulated.

The work proposed in this paper is novel since no one has combined (to our knowledge) retailer power and MCPs and has the following advantages: it solves together the optimality conditions of rival electricity retail firms; it can be extended to a larger number of competitors; it allows identification of an equilibrium among suppliers and avoids interaction through constraints which might cause solution in the form of many equilibria [4]; and finally - it refers to a real market - a highly competitive Nordic electricity retail market.

Electricity retail competition within the Nordic region has so far been focusing on the electricity retail contracts. However, it can be expected that retail competition will take new dimensions as smart metering services and other components of the smart grid (e.g., electrical vehicles, storage facilities, micro-generation) get more common. The three main types of contracts that retailers offer are: 1. a fixed-price tariff that may be for various periods (usually one, three or five years), 2. a spot price tariff and 3. a variable price tariff. Figures 1 and 2 represent the price changes and percentage division for Norwegian electricity retail contracts from 2012 to 2014. The spot price contracts are the ones that experience the greatest variation in prices, but at the same time represent the largest share. The retailers' profits from spot price contracts are dependent on the price markup they set in advance and that is to be added to the wholesale price of electricity. And while the spot price tariff excludes the risk premium[3] retailers get from the fixed and variable price tariffs [15] and is being chosen by increasing number of customers, the severity of retail competition pushes the price markups low. In this paper we consider a future electricity market for which the spot price contracts (or real- time price contracts - as the smart grid functionalities allow for such) have the largest share (also suggested in Figure 2), and for which the price markup will be an important competition tool.

[3] A fixed (or variable) price tariff normally consists of two components: the price of the electricity commodity and the risk premium that consumers pay for being protected from volatile prices.

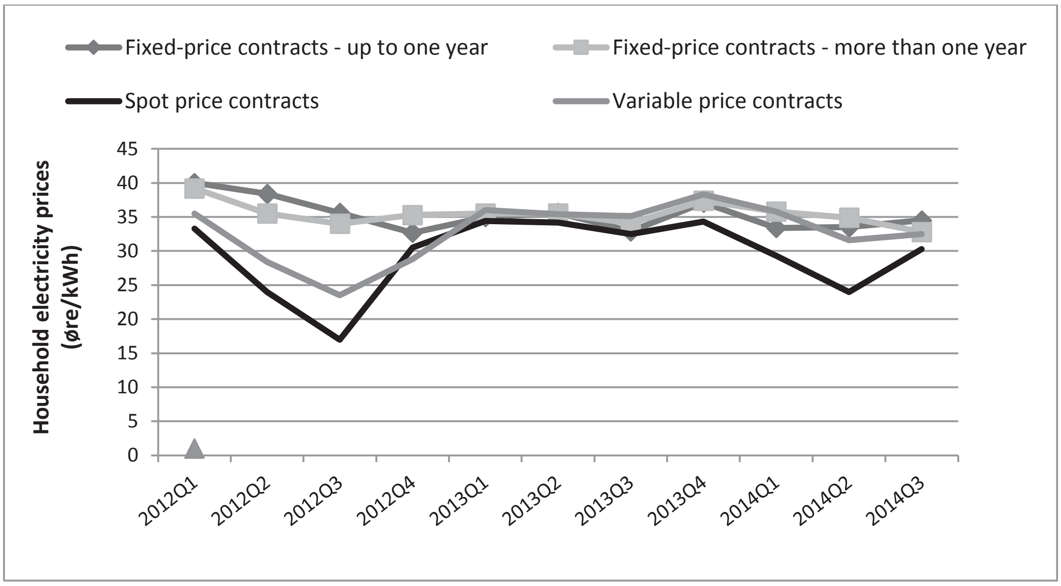

Figure 1 – Household quarterly electricity prices per contract (without taxes) for Norway. *Data source: Statistics Norway*

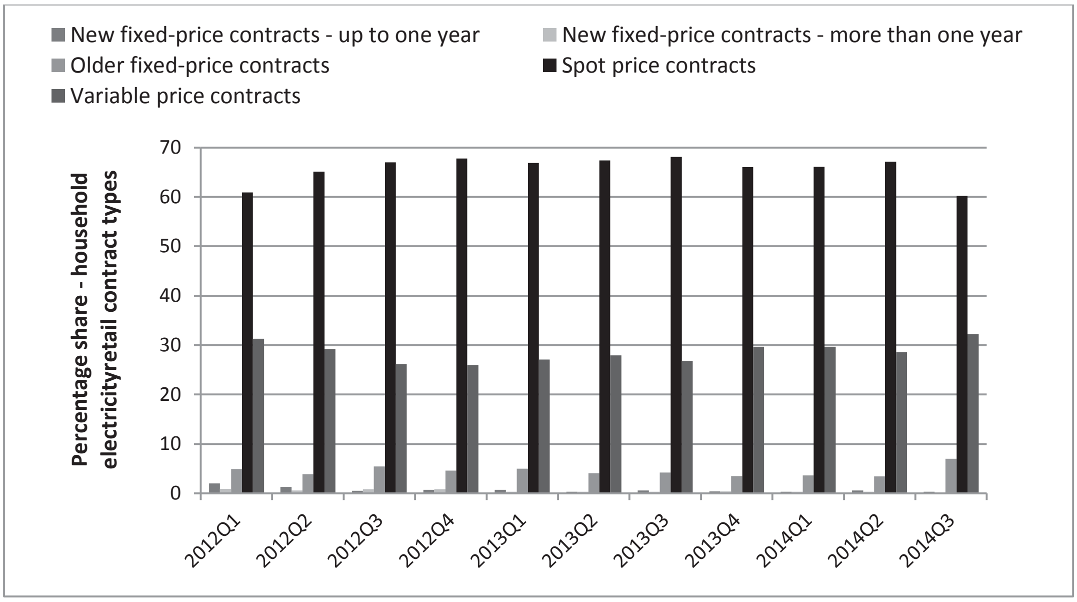

Figure 2 - Percentage share of household electricity retail contract types for Norway – quarterly. *Data source: Statistics Norway*

Another result of the intensified competition within the Nordic end-user market is the increased differentiation of retail products and improved service. Electricity retailers have to balance their portfolio of retail products and services, while keeping their offers attractive to customers and being profitable. As Ilieva and Gabriel [1] discuss, the technological development related to the smart grid will allow for a significant increase in the variety of electricity retail services offered to end-users. And indeed, electricity retailers are being more innovative in developing their offers – they create new electricity products, they combine electricity with other services, advertise rebates and customer programs and give way to new trends in their offers (such as charging of electrical vehicles, micro-generation, and others).

In this paper we focus on the Norwegian electricity retail market (as part of the future common Nordic end-user market) and with the help of a complementarity model we analyze the impact of the pending market changes on electricity price markup and profit. Although the data used in the model represents specifically the Norwegian market, the results and conclusions provided can be useful to other regions where retail market integration and intense smart grid development can take place. The rest of the paper is structured as follows: Section 2 presents the nomenclature and the mathematical model that is based on the retailers' optimization problems; Section 3 describes the data used in the model; Section 4 contains the results from different model simulations together with a discussion on them and Section 5 provides conclusions.

2. MODEL

2.1 Notation and definition

The model used in this paper represents a modification of the model applied by Ilieva and Gabriel [1] but with the notation and definitions kept the same for consistency. The most important new features of the transformed model are: use of new approach when defining service through system of weight points and real data on Norwegian electricity retailers; stochasticity in the market base realizations is excluded; the price markup is presented as dependent on service with the help of real data and econometric estimation. The following notation is used in the mathematical model presented in Section 2.2:

Variables:

Δ_i Price markup for spot price contracts offered by retailer i; $\Delta_i = P_i - P_{sm}$ where P_i is the final, tax-free price offered by the retailer and P_{sm} is the spot market price. While P_{sm} represents data coming from the spot market, P_i is a variable that depends on what is chosen by the retailers price markup Δ_i. The price markup is measured in øre/kWh. However, the measure kNOK/GWh (thousand Norwegian krone per GWh) is used within the model to ease the calculations. The equilibrium price markup is Δ, where $\Delta = \Delta_i = \Delta_j$

s_i Service level for retailer i. The method for quantifying the service level is based on a system of weight points that comprise a proxy for the service level variable. The method has been explained in detail in Section 3.1. In this paper we use the term "service level" as a shortened variant of "level of the proxy for service".

Parameters:

q_i Electricity retailer's market base that is the total number of customers that use a product or a service offered by the retailer. For modeling purposes we transform q_i into a GWh measure. [4]

α Own-price demand sensitivity (GWh), $\alpha \geq 0$

β Cross-price demand sensitivity (GWh), $\beta \geq 0$

η Demand sensitivity for the products and services of one retailer in response to own service level (GWh), $\eta \geq 0$

μ Demand sensitivity for the products and services of one retailer in response to the other retailer's service level (GWh), $\mu \geq 0$

ξ_i Service investment efficiency coefficient for retailer i, $\xi_i > 0$. The higher the value of ξ_i, the less efficient the investment is in cost terms.

z y-intercept of the "price markup versus service" curve (øre/KWh). The value is defined through econometrically estimating equation (4) below and with the help of real data on Norwegian electricity retailers.

θ Slope in the "price markup versus service" curve (øre/KWh). The value is defined through econometrically estimating equation (4) below and with the help of real data on Norwegian electricity retailers.

Intermediate values (calculated from the main variables):

π_i Profit from price markup for retailer i (million NOK)

$\overline{\pi_i}$ Profit from price markup for retailer i, net of service investment costs (million NOK)

d_i Electricity demand satisfied by retailer i (GWh)

The model to be presented in the next section is considered for a typical hour in the year. As the price markup is set independent of the peak/off-peak prices in the spot market ($\Delta_i = P_i - P_{sm}$) the model is of relevance for both peak and off-peak periods. Other temporal aspects (such as daily, weekly, monthly, yearly variations), have been purposely suppressed to make it easier to analyze several scenarios. If the model should consider the peak and off-peak periods separately then P_{sm} has to be substituted by e.g., P_{sm}^{peak} (the average spot price during peak hours) and P_{sm}^{off} (the average spot price during off-peak hours).

[4] The yearly market base (GWh) equals the number of customers multiplied by the average yearly electricity consumption of 0.02GWh per Norwegian household.

2.2 Retailers' optimization problems

In this section we present the optimization problems faced by two competing retailers. Both of them aim to maximize profit and make decisions on the price and service they offer to customers. The duopoly assumption simplifies the modeling procedures and makes it easier to understand how the step towards market integration and service differentiation will impact a single retail company. Yet, as presented in equation (7) below, the model could be extended to a larger number of competitors. In the formulations below, equations (1) to (3) are similar to the ones used in [1]. Having assumed that the spot price contracts will constitute the prevailing part of retail contracts, the spot price contract-based profit will be dependent on the price markup and the demand satisfied.

$$\pi_i = \Delta_i d_i \tag{1}$$

Where d_i can be defined in the following way:

$$d_i = q_i - \alpha\Delta_i + \beta\Delta_j + \eta s_i - \mu s_j \tag{2}$$

In equation (2), the demand d_i satisfied by retailer i depends positively on its own service level s_i and the rivals' price markup Δ_j , and negatively on its rivals' service level s_j and its own price markup Δ_i.

Defining the cost of investment in service by $\mathrm{c_i(s_i) = c_i = \xi_i s_i^2}$, the price markup profit of retailer i , net of service investment costs is:

$$\overline{\pi_i} = \Delta_i d_i(q_i, \Delta_j, s_j; \Delta_i, s_i,) - \mathrm{c_i(\xi_i; s_i)} \tag{3}$$

Additionally, we assume that the price markup and service decisions of two competing retailers are mutually dependent in the following way:

$$\Delta(s_1, s_2) = z - \theta(s_1 + s_2) \tag{4}$$

Previously, we considered Δ_i the markup specific to retailer i. Now, in equation (4), we assume that there is just one markup Δ for all retailers i, along the lines of intensified competition and markups that both decrease and converge as discussed in [16]. Thus Δ represents the equilibrium price markup to be discussed further in the analysis in Section 4.

In equation (4) Δ is presented as a function of s_1 and s_2, and the function is defined by the linear term $z - \theta(s_1 + s_2)$. Equation (4) is intuitively similar to the (inverse) market demand function, presented by Gabriel [17] as $p(q_1 + q_2) = \gamma - \delta(q_1 + q_2)$ where $\gamma, \delta > 0$ and the price of the produced good p accounts for both producers' production levels $(q_1 + q_2)$. In (4) the price markup is dependent on both retailers' service level $(s_1 + s_2)$ and the parameters $z, \theta > 0$. The service level s_i for each retailer represents the sum of weight points each one having a value of 0 or 1, given if the retailer offers a certain product or service (e.g., a retailer that offers only 3 different products: a fixed price tariff, a spot price tariff and broadband installation will have a service level of 3). The method used for the calculation is described in detail in Section 3.1. In the simulations the values for service level are constrained by an upper value (cap_{s_i}) that accounts for the retailers' challenge to innovate on a short-term basis. Substituting Δ_i and Δ_j from equation (2) with the expression on the right hand side of equation (4), and then plugging in equation (2) into equation (3) we get the following optimization problems (maximizing $\overline{\pi_i}$) for a two-retailer case:

For retailer 1: (5)

$$\operatorname*{Max}_{s_1} \, [z-\theta(s_1+s_2)]\big[q_1-\alpha\big(z-\theta(s_1+s_2)\big)+\beta\big(z-\theta(s_1+s_2)\big)+\eta s_1-\mu s_2-\xi_1 s_1^2\big]$$

$$\text{s.t. } s_1 \geq 0, s_1 \leq cap_{s_1}$$

For retailer 2: (6)

$$\operatorname*{Max}_{s_2} \, [z-\theta(s_1+s_2)]\big[q_2-\alpha\big(z-\theta(s_1+s_2)\big)+\beta\big(z-\theta(s_1+s_2)\big)+\eta s_2-\mu s_1-\xi_2 s_2^2\big]$$

$$\text{s.t. } s_2 \geq 0, s_2 \leq cap_{s_2}$$

The objective functions in (5) and (6) represent maximization of the equilibrium price markup profit net of service investment costs $\overline{\pi}$ which is calculated in the model in million NOK. The case for n competing retailers and the Karush-Kuhn-Tucker (KKT) conditions to form the MCP are presented in Appendix A.

To get the resulting complementarity problem it is necessary to solve the KKT conditions for Retailers 1 and 2 (presented by (A.2) and (A.3) in Appendix A) simultaneously. The value of the equilibrium price markup is calculated to reflect the dependence on service level (as indicated by equation (4). The complementarity problem is solved by using the GAMS software with the PATH solver [18].

3. DATA

The data used in the model is based on our own estimations, assumptions related to real market data and other studies and reports ([19], [20]). In this section we present the origin of the data together with its values.

3.1 Quantifying service

In [1] the service level is presented by an investment value in thousand NOK. In the current paper, the approach to service is significantly different. A proxy for service is created by assigning a weight of 1 or 0 points if the retailer has or doesn't have a certain product/service in its offer. Additionally, each of the retail contracts offered by the retailer gives them one point and each innovative “smart grid service” (such as the ones related to own micro-generation, charging of electrical vehicles (EV) and real-time metering) provides one point as well. It is important to note that equations (8) and (9) solve for continuous-valued service levels s_i and s_j which represent a generalization of the integer-valued weight-based approach described above.

To estimate the service level variable real data on 40 Norwegian electricity retailers has been collected and analyzed. Those 40 companies were collected among the total number of electricity retailers in Norway as they had spot price contracts (among others) in their product portfolio. Considering the large share of spot price contracts in the Norwegian end-user market, we regard the existence of such contracts for the selection of electricity retail companies as a necessity.

The proxy approach for quantifying service is summarized below:

Table 1 – Criteria used in quantifying service

#	Retailers' product/service offers	Weight
1	Electricity retail contracts	1 per each contract
2	Electricity distribution	0 or 1
3	Electricity generation	0 or 1
4	Broadband	0 or 1
5	Heat pump	0 or 1
6	Special renewable energy programs	0 or 1
7	Customer loyalty/bonus programs	0 or 1
8	Electric services	0 or 1
9	Entrepreneurship	0 or 1
10	Distance heating	0 or 1
11	Installation services	0 or 1
12	Company newspaper/magazine	0 or 1
13	Bio heating	0 or 1
14	Smart services (EV, micro-generation, etc.)	1 per each service

In order to determine the cap on service, we use the data classification from Table 1 above. Specifically, the maximum number of service points for a retailer is calculated to be 11. This number is derived in the following way - the total sum of the weight points assigned to the retailers' product/service offers (numbered 1 to 14 in Table 1). Among the selected electricity retailers each retailer offers a minimum 1 and up to 9 retail contracts. These are classified as the retailers' product/service offers numbered 1 in Table 1 and include various modifications of the three major classifications: spot, variable and fixed price – e.g. spot price with guarantee, monthly price with winter guarantee, web-based/online tariff, combined tariff, fixed tariff for a certain period (1, 2, 3 or 5 years), spot price giving rebate when buying favorite fruit, spot price combined with a daily newspaper, CO_2-free/green tariff, and more. As a result the selected electricity retailers have been assigned minimum values of 2 and maximum values of 11 for the proxy service level variable for each retailer. These values satisfy the conditions $s_{1,2} \geq 0$ from equations (5) and (6).

Besides the calculations for determining the service level for each retailer in the data, we consider the total set of contracts and services for all retailers. This is the total number of different weight points collected in the estimation process of all retail products and services and for all retailers. This total number sums up to 23 and includes the 9 modifications of retail contracts, 12 weight points for the products numbered 2 to 13 in Table 1 (1 point per each product/offer), and 2 types of smart services. The data used as a basis for constructing the proxy for service has been collected during December 2014. The total number of weight points (23) is used to define the cap on service in a Base Case simulation presented in Section 4. However, the possible future increase of the service level (for example as a result of offering additional services related to smart metering) will be discussed in a consequent scenario where the cap on service is varied.

The relationship between the price markups in the electricity retailers' spot price contracts and the proxy service variable has been investigated. The purpose is to find realistic estimates of the parameters z and θ, as presented in equation (4), with the help of econometric estimation. Assigning z (the intercept) the lowest price markup value (0.84 øre/kWh) and econometrically estimating the slope θ to be 0.07, we can proceed to defining the rest of the model's parameters.

3.2 Demand to be satisfied by electricity retailers

Unlike in [1] where demand was defined by calculating the probability of a certain market base value to occur, in this paper the market base q_i is treated as a parameter whose value represents the average for all electricity suppliers in Norway. Yet, in the model simulations, the assumptions for the demand base are varied to account for the differences between large and small retail companies. The demand base is calculated in the model as $q_i = 0.02N_i$ where N_i is the number of household customers per retailer (as estimated by the Norwegian Water Resources and Energy Directorate in 2012), and 0.02 is the yearly GWh consumption that the Norwegian Competition Authority assumes the average household in the country has. In the model simulations' Base Case $q_1 = q_2 = 405$ GWh.

3.3 Parameters for sensitivity

The cross-price elasticities α and β, and the elasticities of demand in response to service level η and μ come from the study by Halvorsen and Larsen [19] on Norwegian households. The numbers that we use are explained in detail by Ilieva and Gabriel [1]. To be consistent with our previous research, the sensitivity values are originally kept the same but are later changed in a model simulation to investigate the effects of a change in end-users' attitudes. The starting values are as follows:

$\alpha = 0.0046$ $\qquad\qquad$ $\beta = 0.0034$

$\eta = 0.0067$ $\qquad\qquad$ $\mu = 0.0058$

3.4 Investment efficiency coefficient and cap on service level

With the assumed values for α and η in Section 3.3 and considering the convexity condition from Section 2.2: $2(2\,\beta\theta^2 - \alpha\theta^2 - \eta\theta + \mu\theta)(\xi_2 - \xi_1) = 2C(\xi_2 - \xi_1) \geq 0$, the value of $\xi_1 = \xi_2 = 0.01$ is chosen for the Base Case scenario. The cap on service level is set to the maximum number of different weight points (for all retailers and for all services) collected in the estimation process of the retailers' service level per December 2014. Thus, in the Base Case $s_1, s_2 \leq 23$. But as we expect that the end-user market processes related to the development of the smart grid will stimulate offers of new products and services we allow for increase in the cap value in a following simulation.

4. RESULTS AND DISCUSSION

In this section we develop and discuss the results from the model simulations. The purpose is to observe and analyze how changes in the model parameters affect an equilibrium solution, and what would be the effects on retailers' yearly profits.

4.1 Equilibrium solution in the Base Case

The data used in the Base Case scenario have been already described in Section 3. With an expected demand of 405 GWh for each of retailers 1 and 2, an equilibrium price markup on the duopoly market is 4.06 øre/kWh and the profit is 16.443 million NOK. Both retailers choose the maximum level of service $s_1 = s_2 = 23$. The price markup when the retailers decide to offer the full range of products and services (4.06 øre/kWh) is almost five times higher than the minimum price markup found in the market from December 2014 (0.84 øre/kWh). This fact questions the extent to which customers will be interested in paying more in order to get better service. And if they choose to do so, the savings or benefits associated with the improved service should compensate for the increased payments they have to make. In addition, the shadow price of the constraint $s_i \leq cap_{s_i}$ indicates an increase in profit by 17% when relaxing the constraint on service cap_{s_i}. Clearly, retailers that manage to innovate above the products and services currently available on the market (e.g., through offering new services related to the smart grid) will increase profits significantly. In Section 4.1.1. we observe further the impact of service level by integrating the change in the cap on service in the modeling procedures.

It is important to note that these results assume that two retailers operate under the same conditions and have an equal market base, and that the value of each product/service has an equal weight. However, in the real world the retailers differ from each other in many ways. In the model simulations to follow we will discuss how the differences to be found in the retailers' market environment and strategy will impact the price markup and profit in the equilibrium solution.

4.1.1 Markup and profit when the maximum service level varies

Taking the Base Case scenario as a reference, we observe the service level's impact on the equilibrium price markup and profit. In the course of 20 iterations we increase the cap on service level with 1. The value of cap_{s_i} in the first iteration equals the maximum value of the service variable found in the data $s_i = 11$. Each iteration represents a repetition of the process of solving the optimization problems (5) and (6) but with cap_{s_i} changing on every step. The corresponding results are presented in Figure 3. The price markup increases from 2.24 to 4.9 øre/kWh while the profit rises from 9 to nearly 20 million NOK. It should be noted that in the real data a retailer with service value of 11, also used as a starting value in the iteration process, does offer a price markup of 2.3 øre/kWh - a number that stands pretty close to the model results of 2.24 øre/kWh.

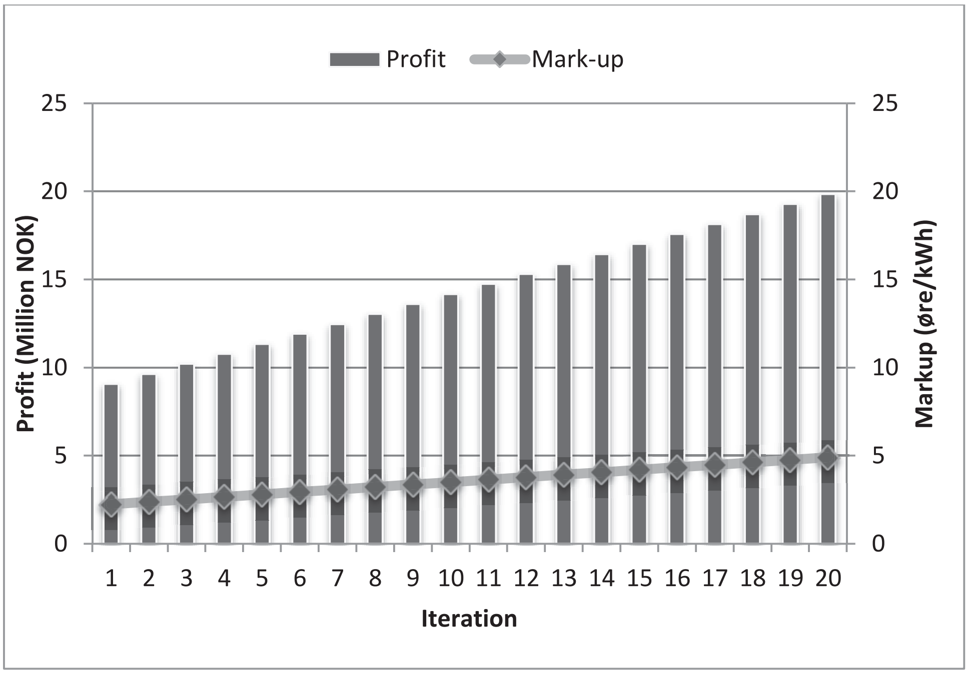

Figure 3 – Profit and price markup when the cap on service level increases

4.2 Competition between retailers of different size

In this model simulation we look at a duopoly market in which the retailers have a different market base q_i and respectively different demand to cover. Retailer 1 with a market base calculated as the average of the 20 smallest retailers in Norway is compared to retailer 2 with a market base of the 20 largest retail companies. The cap on service is kept at 23 weight points and the sensitivity values, the efficiency coefficient and the slope and intercept parameters are as in the Base Case. In the course of 20 iterations the market base of retailer 1 is increased by 20% while that of retailer 2 decreases by the same percentage. Table 2 presents the results.

Table 2 – Retailers' yearly profit when demand changes: small versus large retail company

Iteration	Demand 1 (GWh)	Demand 2(GWh)	Profit 1 (Million NOK)	Profit 2 (Million NOK)
1	16.08	1436.8	0.65	58.33
2	19.30	1149.44	0.78	46.67
3	23.16	919.55	0.94	37.33
4	27.79	735.64	1.13	29.87
5	33.34	588.51	1.35	23.89
6	40.01	470.81	1.62	19.11
7	48.01	376.65	1.95	15.29
8	57.62	301.32	2.34	12.23
9	69.14	241.06	2.81	9.79
10	82.97	192.84	3.37	7.83
11	99.56	154.28	4.04	6.26
12	119.48	123.42	4.85	5.01
13	143.37	98.74	5.82	4.01
14	172.05	78.99	6.99	3.21
15	206.45	63.19	8.38	2.57
16	247.74	50.55	10.06	2.05
17	297.29	40.44	12.07	1.64
18	356.75	32.35	14.48	1.31
19	428.10	25.88	17.38	1.05
20	513.72	20.71	20.86	0.84

Clearly, the size of the market base has a huge impact on profit. And if through improved service a retailer manages to gain more customers, it may considerably increase its benefits. The retailers are almost equally well off in the 12th iteration where profit is of approximately 5 million NOK and the demand to be met is close to 120 GWh. To cover the total electricity demand of 2249541 Norwegian household customers that have an average yearly usage of 0.02 GWh, there will be needed 374 retailers if they are to have profit of a similar size to the ones presented in this model simulation. This huge number of retailers is different than at present. In fact, the total number of Norwegian electricity suppliers is 82, out of which only around 30 operate nationwide. Considering the rest of the Nordic countries Finland, Denmark and Sweden with respectively around 80, 50, and 100 retail companies a total of over 300 retailers to sell electricity within a common Nordic end-user market is perhaps more realistic.

Although during the last years the number of electricity suppliers covering the whole Nordic market has been increasing for most countries (Figure 4), this trend can be counteracted by mergers and by companies who lose their business due to the more severe competition in the greatly increased market area. The attractiveness of retail products and services will be decisive for how well the retailers position themselves, and what profit and market base they manage to gain. Some companies have already built big market bases by offering discount packages for multiple home services including gas, electricity, mobile and home phone, broadband, and various insurances [21].

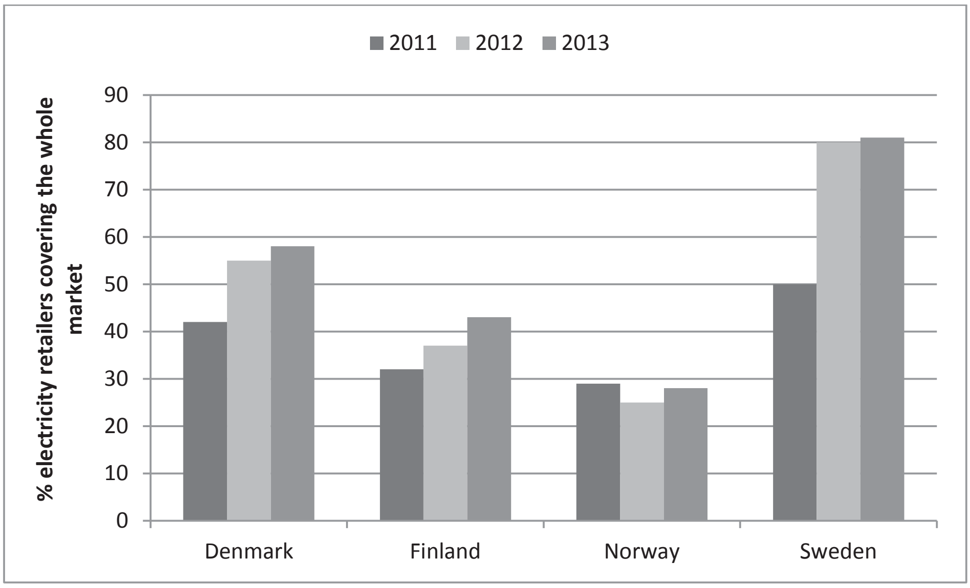

Figure 4 – Percent of electricity retailers that operate nationwide for the period 2011-2013. *Data source: Nordic Market Report, NordREG [22]*

Using an MCP setting to solve the optimization problems of two competing retailers helps improve the modeling procedure in one important way: the method provides a comprehensive mathematical representation of the retail market equilibrium conditions, featuring both inequalities and complementarity. The shadow prices on the service cap constraint found in this section's model simulation indicate a 22% increase in profit when a small retailer competes versus a big one. The value is 5% above the shadow price found in the Base Case scenario. Although the model simulations are based on a number of assumptions, the results for the shadow prices suggest that the profits of equally innovative electricity retailers will be increasing by less in the case where retailers within a common Nordic market are converging in size. On the contrary, if the competing retailers differ significantly in size, the profit of each of them will increase by more if retail product innovation is present.

In a sub-case of this model simulation the cap on service for retailer 1 is lowered to 11 (the maximum sum of weight points currently existing in the Norwegian market for a single retailer – see Section 3.1). As a result the equilibrium price markup is decreased from 4.06 to 3.22 øre/kWh and the profits of both retailers are lower. Retailers that are skeptical to innovate in service may thus impose pressure on the retail sector by pushing the price downwards.

Obviously, in an oligopolistic end-user market, a retailer that chooses to offer a lower service level may push the equilibrium price markup downwards. The lower price markup will decrease the profits of other retailers as well. Yet, these market adjustments will be even more important within a common Nordic retail market setting when a much higher number of retailers will have the chance to interact with the customers and influence each other. The price markup decreases by 20.7% when retailer 1 chooses the lower service level. In general, electricity retail companies may have to compete more intensively to keep a sufficient customer base (and respectively profit) when new smart grid technology becomes easily available and when end-users become aware of its benefits. As the smart grid penetrates the power system and as electricity end-users' knowledge increases (and their focus moves from price to service offers), we can expect a Nordic retail market transformation of a similar form.

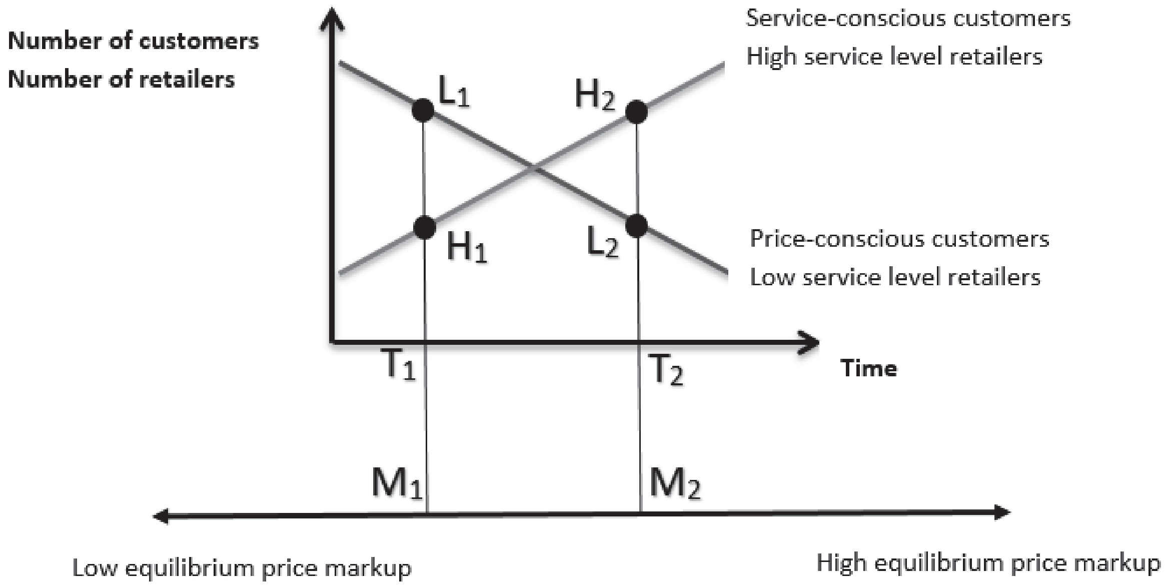

Figure 5 – Transformations in the future Nordic end-user market for electricity. The upper x and y axes represent time versus the number of customers/retailers while the axes below represents the price markup.

At time T_1, in Figure 5, the number of price-conscious customers and low service level retailers (point L_1) is higher than the number of service-conscious customers/high service level retailers (point H_1). The equilibrium price markup at this market state is M_1. At a future time state T_2 the number of service-conscious customers/high service level retailers is higher (point H_2) and the equilibrium price markup is M_2 ($M_1<M_2$). In Figure 5 the total number of customers/retailers at time T_1 is equal to that in time T2 ($L_1 + H_1 = L_2 + H_2$). This is a strong assumption and in fact it is hard to predict the future number of retail companies. Although some experts are on the opinion that the total number of electricity retailers will go down as competition becomes intensified [23] there are some trends to work in the opposite direction – the generally increasing number of electric power providers within a common Nordic end-user market, and subsidiaries formed by incumbent companies in order to specialize in promoting and trading retail products and services.

4.3 The impact of increasing end-users' knowledge

During the last few years, the research interest about electricity consumers' attitudes and knowledge has increased. Consumers are expected to play a key role in an efficiently operating smart grid and not surprisingly, a number of scientific articles have focused on consumers' attitude and engagement – e.g., [24], [25], [26], [27], [28]. From a passive market actor that only pays for the electricity consumed, the end-user is being asked to take a more active role by choosing among a variety of contracts and by observing and managing its own consumption. But as [29] show, electricity consumers have heterogeneous preferences for electricity retail products and the needs of the various segments of consumers can be satisfied by differentiated retail offers. Furthermore, the preferences and attitudes of electricity consumers in Europe have been examined in pilot projects, which , as discussed by [24], have two main purposes: to gain better knowledge on consumers' behavior and to motivate and empower the end-user to be more of an active participant in the power system. With all these research activities as a background we could expect that consumers' knowledge will increase, and they will make more informed decisions when choosing which retail products and services to pay for. In this context the sensitivity coefficient θ (equation (4)) might increase its value - a change that will account for consumers' preferences on service and how these will be related to the price markup they face.

In connection to the above reasoning in this model simulation the coefficient on θ is varied. In addition, we make an assumption that innovative services are to be bundled with spot price/real time price contracts. An increase of θ by 10% in the course of 20 iterations shows that if customers increase their awareness and begin to value services more than before, the price markup can become significantly higher (Figure 6). This will contribute to a more than four times increase in a retailer's price markup profit, net of service investment costs. Yet, in the Nordic region with a high amount of regulated hydropower in the generation portfolio, the electricity prices are already low and the common market setting with intensified competition may push the markups on spot price/real time price contract downwards. Therefore, an increase in the markup can be expected predominantly under the condition that new services are present in the retailers' portfolio and that these are valued by the customers more than before.

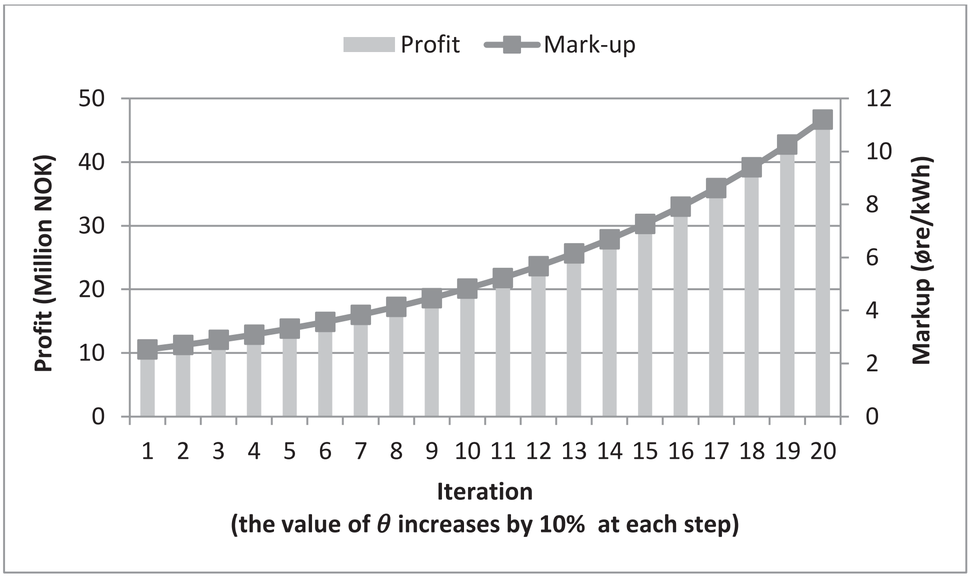

Figure 6 – A retailer's price markup and yearly profit when θ increases

In addition, we look at the link between the price markup and profit effects of an increase in θ and the main assumptions in the model simulations presented in Sections 4.1 and 4.2. In the case where retailer 1 has the average market base but a higher capability to innovate (higher cap on service) and retailer 2 has higher market base but lower capability to innovate (lower cap on service), the percentage increase in retailer 1's profit is only slightly higher than that of retailer 2. The change in shadow prices is very small – 1.4% increase in the shadow price on the service cap constraint for the averaged-sized retailer and 0.2% increase for the larger in size one. This indicates that the level of service has a limited effect on profit when the price markup to service parameter θ increases for both retailers.

Yet, as consumers' knowledge increases, we may expect a bit bigger increase in the profit for the smaller in size but highly innovative retailer. Figure 7 represents the relationship between service level, change in profit and theta for an average-sized retailer for which the cap on service is being allowed to increase above 23 weight points (the maximum sum of all service weight points for all retailers – see Section 3.1). In this simulation the average-sized retailer is competing with a larger in size retailer which has a lower cap on service (up to 11 weight points). The percentage changes in profit are largest for the highest maximum service level values. However, the change in profit has a different relation to theta and starts declining after the 11[th] iteration. Thus, it may be expected that innovative retailers will have moderately increasing profits after an optimal combination of θ and cap_{s_i} is met.

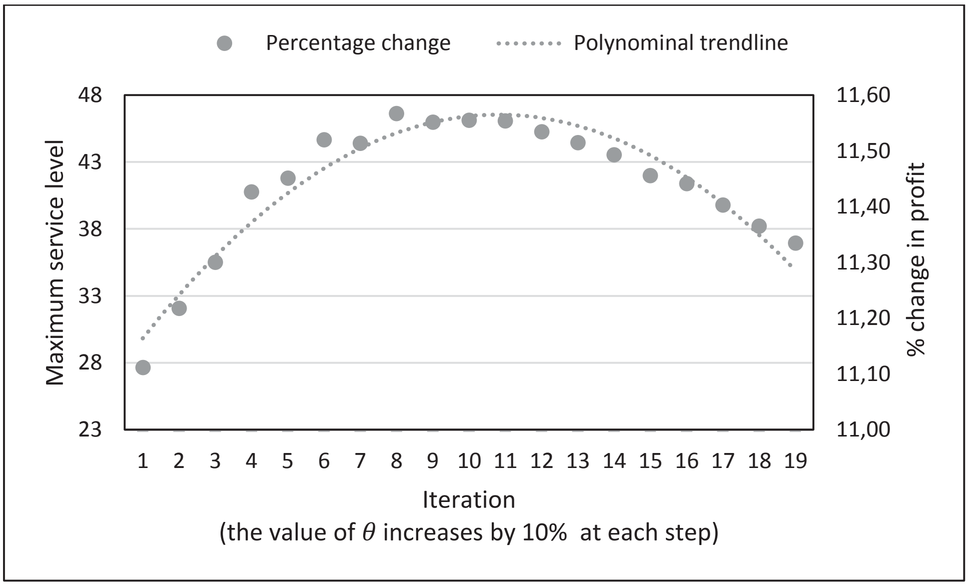

Figure 7 – The relationship between maximum service level, percentage change in profit and θ for an average-sized retailer.

4.4 Demand flexibility in the retailers' product portfolio

During the past decade the amount of power generated from renewable energy sources (RES) has increased significantly as a consequence of climate change consideration. To successfully manage a grid where the electricity production is strongly varying (e.g., due to intermittent solar and wind power) it is important to have flexible demand. The value of demand flexibility for Norway and the North European region has been discussed by [30], who show that flexibility in electricity consumption can bring system benefits and increase the profits for the producers of renewable energy. Currently, however, the extent to which demand flexibility offers are present in the retailers' product portfolio is limited. Thus it may be expected that the retail offers to simulate flexible usage will increase as the share of RES used in the generation gets higher.

Although the Nordic region has over 50% of its electricity generated by regulated hydropower plants and the shares of nuclear and fossil are respectively 23% and 12%, during the last years the amount of wind power-generated electricity has been increasing by about 20% (4TWh) yearly [22]. Considering its transmission cable connections to other countries with growing amounts of intermittent energy, such as Germany (solar power), the need for demand flexibility as a resource to effectively balance the power grid flows is expected to increase.

More flexible consumption will mean a change in the own-price and cross-price sensitivity coefficients α and β. If in the Base Case scenario presented in Section 4.1 the values of α and β are increased by 10%, the new equilibrium price markup and profit will be of respectively 2.38 øre/kWh and the equilibrium profit will be 9.64 million NOK. In the Base Case solution the equilibrium price markup and profit are considerably higher: 4.06 øre/kWh and 16.44 million NOK. The increase in demand flexibility will push the price markup value downwards, and this will decrease retailers' price markup profits. However the increase in flexible consumption will open new possibilities for the retailers – as an example they can get paid for assisting customers in their flexibility choices, or make profits from selling the flexibility options the customers possess. In the Nordic Energy Regulators' plan for the development of a common Nordic end-user market the combination of a "supplier-centric model" and a data hub through which metering data can be accessed are crucial for increased competition [31]. The idea behind a supplier centric models and a data hub solution is that the end-user will only communicate with the retailer, while the distribution system operators will feed in data into the hub. The data can then be accessed by the suppliers for billing and settlement purposes, by the tax authorities and by the transmission system operators.

Undoubtedly electricity retailers will play a major role in the future end-user market of the Nordic region. Besides their main profit-making tool – the electricity price offered to end-user, changes in the power system structures, such as introduction of smart metering, data hub and common market, the suppliers of electric energy may benefit from employing new concepts in their business. These can be bundling of electricity and other services, taking on a role of an aggregator that trades demand flexibility and the loads of customers with own generation or selling certain volumes of electricity with the option to buy part of them back.

Such services are already offered by retail companies in other parts of the world. For example, in the UK, Australia and New Zealand where electric power suppliers combine electricity delivery with non-traditional services to ensure customer loyalty and where customers are increasingly requiring flexible billing solutions [21]. Within the common Nordic end-user market the service innovation level can get a significant push forward as a result of increased competition and the challenges related to satisfying the need of the modern “smart grid aware” electricity consumer. In addition, when it comes to the Norwegian electricity suppliers, among the various products and services offered (as presented in Table 1), the contracts related to “green energy” are gaining popularity. With the increasing environmental considerations by society we may expect this trend to persist.

4.5 The model’s contribution to the retailers’ strategic decisions

The applied in this paper model aims to assist the retailers in developing better service and supporting their planning functions. The model may help for the decision making process at electric retail companies in the following ways:

- The model allows to find an optimal combination of price markup and service in the retailer’s portfolio of offers and to easily observe the effect of changes in the sensitivity coefficients
- The model can be modified so that the sensitivity values correspond to a given electricity retail company and also extended to include the price markup and service decisions to all its rivals. Then the retailer can use the model for optimizing profit based on own price markup and service offers.
- The model may support the price markup and investment decisions by providing insight on the changes in the equilibrium price markup and profit.

5. CONCLUSIONS

In this paper’s model simulations we observe the changes in the equilibrium price markup and profit for two electricity retailers that are subject to specific market conditions. We reflect on two major motivators for changes in the electricity retail market environment: market integration and the development of a smart electricity grid. The first factor – the establishment of a common Nordic End-user market, is decisive for the market base they get and the extent to which they choose to innovate in order keep their existing customers or attract new ones. The second one – the smart grid, has the increase in customers’ awareness and knowledge as a prerequisite for its successful operation. Formulating and solving a complementarity problem we observe the impact of various changes in the model parameters in several consequent simulations. The model applied could assist the retailers’ strategic decisions by providing a simplified profit optimization framework in which service level is quantified by a system of weight points and where sensitivity values are used to reflect retailers’ attitudes to price markup and service.

In the case where retailers choose to offer the full range of services currently existing in the joint portfolios of Norwegian suppliers, the equilibrium price markup experiences a five-fold increase when compared to the minimum price markup in the market. If price markups for the spot-price contracts do increase as a result of improvement in the service level, the customers will have to get sufficient service-related benefits or savings as compensation. Under the strong assumption of an equal market base for the competing retailers, the equilibrium profit and price markup increase as the service level gets higher.

Running the model for retailers with different market bases, we observe how strongly the quantity of demand to be satisfied impacts an equilibrium solution. Not surprisingly electricity retail customers are subject to increasing number of advertising experiences: phone calls, e-mails, post letters that provide information on new offers and are meant to motivate change of contract/supplier or keep the existing customers by providing service packages and rebates. Also, as the shadow prices from the MCP indicate, in a market where the retailers are of similar size, innovation will contribute with less to each retailer’s profit, than when compared to a retail market in which the retailers’ size differs significantly. As customers gain knowledge and become aware of the possibility for specific electricity usage options made available within a smart grid environment, the role of electricity retailers as a mediator to provide for smart metering associated benefits and efficient consumption will increase. Innovative electricity retailers with higher service level will thus be able to sell new products that utilize the opportunities offered by smart grid to the informed customers. As the model results indicate, knowledge about the smart grid will motivate customers to value new services more than before and innovative retailers will get the chance to increase markups and yield. Yet, the size of the market base remains the most decisive factor for a retailers’ profit.

The effective guiding of demand flexibility at the consumers’ premises through real-time spot price tariffs could push the price markups downwards. The reason for this will be the increasing sensitivity to the prices offered by the competing retailers. On the other hand, the increase in markups that may take place as a result of improved service for the customers on spot price/real time price contracts is of an opposite direction. Thus, the extent to which customers value service and the suppliers’ billing strategy to cover the service-related costs will be decisive for the specific price and service combination. In general, it might be expected that the number of customers who strongly value service will increase. As a result, more retailers may be offering high service levels and the equilibrium price markups will likely be higher.

Undoubtedly, the electric power suppliers in the Nordic region are to face a challenging future. As the complementarity model with 2 competing retailers indicates, the changes associated with market integration and smart grid development will impact the price markups and profits of the competitors. The scope of this impact will be dependent on how well informed and responsive customers are, the level of service retailers choose to offer, what strategy they have to keep existing customers and gain new ones, and the type of market transformation to take place (common Nordic market dominated by retailers of a similar or of a different size). If we are to transfer the model results to a multi-player case we may expect the presence of a first mover (first innovator) advantage and a larger integrated Nordic market where only the "strongest will survive".

APPENDIX A

In this appendix we present the optimization model when n retailers compete in the market as well as the KKT conditions to form the MCP.

The model for n competing retailers represents a generalization of the objective functions used for Retailer 1 and Retailer 2 (as shown by (5) and (6) in Section 2.2). The objective functions (5) and (6) originate from equation (3) where Δ_i is substituted by the respective equation for equilibrium price markup (4), and d_i is represented by equation (2). In the case of n competing retailers, a single retailer's optimization problem (e.g., retailer j's problem) will take the following form:

(A.1)

$$\underset{s_i}{\text{Max}} \left[z - \theta\Big(s_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} s_j\Big)\right]\left[\begin{array}{c} q_i - \alpha\left(z - \theta\left(s_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} s_j\right)\right) + \beta\left(z - \theta\left(s_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} s_j\right)\right) + \\ \eta s_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} \mu_j s_j - \xi_i s_i^2 \end{array}\right]$$

$$\text{s.t. } s_i \geq 0,\ s_i \leq cap_{s_i}$$

In the case of $n = 2$ retailers with a price markup $\Delta = \mathrm{z} - \theta(\mathrm{s}_1 + \mathrm{s}_2)$ the objective functions (5) and (6) are convex as long as $2(2\,\beta\theta^2 - \alpha\theta^2 - \eta\theta + \mu\theta)(\xi_2 - \xi_1) \geq 0$ and consequently the KKT conditions are sufficient for optimality. Clearly, for all $\xi_i = \xi_j$ the convexity conditions will hold. The necessity of the KKT conditions follows from the linearity of the constraints. The KKT conditions for the two retailers are:

For retailer 1:

$$0 \leq \mathrm{A}(\mathrm{q}_1) + \mathrm{B}(\xi_1)\mathrm{s}_1 + \mathrm{C}\mathrm{s}_2 + \lambda_1 \perp s_1 \geq 0 \tag{A.2}$$

For retailer 2:

$$0 \leq \mathrm{A}(\mathrm{q}_2) + \mathrm{C}\mathrm{s}_1 + \mathrm{B}(\xi_2)\mathrm{s}_2 + \lambda_2 \perp s_2 \geq 0 \tag{A.3}$$

Where for $i = 1{,}2$: $\mathrm{A}(\mathrm{q}_i) = 2\alpha\theta\mathrm{z} - 2\beta\theta\mathrm{z} + \eta\mathrm{z} - \theta\mathrm{q}_i$ (A.4)

$$B(\xi_i) = 2\beta\theta^2 - 2\alpha\theta^2 - 2\eta\theta - 2\xi_i$$

$$C = 2\,\beta\theta^2 - \alpha\theta^2 - \eta\theta + \,\mu\theta$$

λ_i is the Lagrange multipler corresponding to the inequality constraint $cap_{s_i} - s_i \geq 0$

In equations (A.2) and (A.3) s_1 and s_2 are variables while $q_{1,2}$ and $\xi_{1,2}$ are parameters the values of which are changing in the simulations for analysis purposes.

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Paper IV

Electricity market impacts of increased demand flexibility enabled by smart grid

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Abstract

This paper analyzes market effects of increased electricity demand response (DR) and investigates how DR could improve integration of large-scale variable renewable energy (VRE). Within-day DR in the future Northern European power system is modeled endogenously in a detailed partial equilibrium model simulating market clearing prices, generation and transmission. We find only minor impacts of DR on average prices and consumers' costs of electricity, but DR reduces VRE curtailment and increases per-unit profit for VRE producers and decrease the residual demand and need for peak power technologies. With the assumed fuel prices, total GHG emissions are found to increase with DR, but this effect is sensitive to fuel and carbon price assumptions. Sensitivity analyses show that DR benefits are generally larger if there is a tight supply-demand balance. The limited benefits for the consumers suggest that policy instruments are needed to enhance price responsive demand.

Keywords

Electricity markets, demand flexibility, variable renewable energy integration, partial equilibrium model

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List of symbols

Symbol	Definition
s, S	Week of the year, $s = \{s_1, s_2, \ldots, s_S\}$, $S = 52$ (total weeks of the year)
n,N	Day of the year, $d = \{d_1, d_2, \ldots, d_D\}$, $D = 364$ (total days of the year modeled)
t, T	Hour of the week, $t = \{t_1, t_2, \ldots, t_T\}$, $T = 168$ (total hours of the week)
h, H	Hour of the day, $h = \{h_1, h_2, \ldots, h_H\}$, $H = 24$ (total hours of the day)
c, C	Country, $c = \{DK, FI, GE, NE, NO, SE, UK\}$, $C = All\ model\ countries$
(r, R),(a,A)	Region, r = $\{Denmark1, Denmark2, \ldots, UK\}$, $R = All\ model\ regions.$ (a,A) is alias for (r,R)
D	Consumer's utility function
d	Electricity demand (MWh)
g	Electricity generation (MWh)
$\bar{g}$,$\underline{g}$	Maximum and minimum power generation level for groups of generation units (MW)
$X^{(a,r)}$	Electricity transmission from region a to region r (MWh)
$\bar{X}$	Transmission capacity limits between regions (MW)
d^{pump}	Energy used for pumped storage (MWh)
ω^{pump}	Water amount pumped back to the hydro reservoirs by pumped storage (MWh)
η^{pump}	Pumped storage energy efficiency (fraction)
i,I	Power generation technology type, $i = \{i_{HY}, i_{IRE}, i_{TH}, i_{NUC}, i_{CHP}\}$
i_{VRE}	Subset of i, variable renewable energy sources $i_{IRE} = \{i_{ROR}, i_{WIN}, i_{SOL}\}$
i_{TH}	Subset of i, thermal (gas, coal and oil) power generation groups $i_{TH} = \{i_{ngas1}, i_{ngas2}, \ldots, i_{oil4}\}$
j,J	Thermal power operating mode based on cycling condition $j = \{low, medium, high\}$
$\underline{ramp}$, $\overline{ramp}$	Maximum capability of hourly up- or down power ramping (fraction of total installed capacity)
K^P, K^T, K^D	Electricity production, transmission and distribution cost (€/MWh)
k_{TH}^{d}, k_{TH}^{c}	Direct production costs and cycling costs of thermal power technologies (€/MWh)
v	Water amount in reservoir at end of time period s (MWh)
ω	Water inflow in time period s (MWh)
$\underline{v}$, $\overline{v}$	Maximum and minimum level of hydro reservoir (MWh)
$\underline{v_0}$, $\overline{v_0}$	Maximum and minimum initial levels for the hydro reservoirs (MWh)
Δd	Up- or downward shift in demand triggered by demand response (MW)
d^{max}, $\overline{d}$	Maximum and average diurnal electricity demand
γ	Potential for demand shifting (percentage)

List of abbreviations

DR	Demand response
RD	Residual demand
VRE	Variable renewable energy
ROR	Run-of-river
IEA	The International Energy Agency
RTP	Real-time pricing
AMS	Advanced metering systems
TSO	Transmission system operator

1 Introduction

The transition to a less carbon intensive power sector implies increased supply of variable renewable energy (VRE) technologies like solar, wind and run-of-river (ROR) hydropower. The supply of VRE is *variable* (determined by weather conditions), *uncertain* (since there are errors in forecasting supply) and *location specific* (the primary energy carrier cannot be transported like coal or biomass) (Borenstein 2012, Hirth et al. 2015), and these characteristics cause challenges related to regulation and balancing of energy systems with high VRE shares (Georgilakis 2008, Franco and Salza 2011, Perez-Arriaga and Batlle 2012). Increased flexibility on the demand side, in the form of adjusting the consumption pattern to variations in supply on a short-term basis, known as demand response (DR), is one way of handling power generation from VRE (Delucchi and Jacobson 2011, Hirth 2013). This has also been acknowledged in the work of who provide an overview of the core issues related to DR (benefit and cost assessments, and implementation) and a literature review of studies that focus on DR and VRE. A case study by the International Energy Agency (IEA) suggests that demand side management is the power system flexibility option with the highest benefit to cost ratio (IEA 2014) for VRE integration.

The short-term DR in electricity markets is currently limited for two main reasons: First, most consumers are not exposed to real-time pricing (RTP), implying that they have no economic incentives to move consumption to periods with low prices. Second, technical solutions for automatic adjustment of consumption are today limited, meaning that flexible - or smart - energy usage requires the user’s action.

Notwithstanding, there are reasons to expect that these obstacles may become less important in the future. The lack of incentives to move consumption can be solved through the development of new electricity retail contracts that motivate price response. The need for such has been extensively analyzed by He et al. (2013) who point out the importance of diversified electricity contracts to match consumers’ preferences and the importance of intermediaries that consumers sign these contracts with. The importance of implementing innovative electricity pricing contracts (such as dynamic pricing) within the regulatory framework has been discussed on governmental level in the EU (European Commission 2014). The necessary changes are seen as feasible given the adequate technology is present. Yet, as noted by Strbac (2008) and Gils (2014), problems related to information and communication infrastructure, lack of understanding of the benefits of DR, increase in the complexity of system operation and potentially other technical, economic, legal and societal issues have to be solved.

Regarding the second obstacle: advanced metering systems (AMS) are currently introduced on a large scale in most European countries, and research and development projects related to their optimal operation and efficient usage are of high interest (Hierzinger et al. 2012). The AMS technology enables an accurate follow-up of consumption and may remove technical barriers for new electricity contract types that provide economic incentives for price responsive demand - e.g., RTP, time-of-use tariffs, critical peak pricing and peak time rebates.

The use of AMS is a necessary but not sufficient factor for better utilization of DR potentials for power system regulation. Other elements of the future smart grid, such as automation and communication technologies and devices and appliances assisting DR, should be present to help consumers in their responsive actions. The research and development efforts of technology vendors and energy companies in the recent years ensure that these elements are already becoming available on the market. As a result, the possibility for electricity consumers to adjust their usage and contribute to private and system benefits is highly increasing.

The effects of RTP on DR have been previously analyzed by Allcott (2011), who evaluates the first program to expose residential consumers to hourly RTP in the US. The study finds a statistically significant price elasticity of electricity demand and that consumers respond to RTP by conserving energy during peak hours. The likely development towards RTP in the Nordic region is acknowledged by Savolainen and Svento

(2012) who analyze the expected market impacts of RTP in the Nordic energy system. By analyzing different elasticity levels and shares of consumers on RTP, they find that RTP reduces the maximum total capacity level required and that peak hour prices clearly diminish as the assumed share of customers on RTP increases.

A few peer-reviewed articles discuss the connection between DR and VRE and the effects that their coexistence can have on the power system: Savolainen and Svento (2012) find that more wind power enters the market when the shares of consumers on RTP increase, and similarly the results of Finn and Fitzpatrick (2014) indicate that shifting demand towards periods with low prices can increase the consumption of wind generated electricity. These findings are in line with Hirth (2013), who identifies demand response in the form of demand shifting as an important flexibility resource that could help to integrate and increase the market value of VRE. Other studies focusing on the DR-VRE connection include: Aghaei and Alizadeh (2013), Stadler (2008), Bouckaert et al. (2014), Wang, Q. et al. (2015), Wang, X. et al. (2015), Tröster et al. (2011), Kohler et al (2010) and others. Still, as noted by Göransson et al. (2014), the literature focusing on the DR effects on a set of heterogeneous power systems constrained by transmission capacities has been very limited.

A development towards increased short-term DR will likely affect three ongoing major public policy debates related to VRE integration, as described by Hirth (2015a): (i) the market value of VRE, which is being depressed when the VRE shares increase due to the temporal and spatial variability of VRE supply; (ii) the technical challenges of integrating VRE into power systems, such as increased need for balancing reserves, more frequent ramping and cycling and ensuring capacity adequacy; and (iii) the impacts of subsidized VRE on profits in the utilities industry and investment incentives through the merit order effect. The aim of this work is to increase the understanding of how increased DR may affect all these three issues in a future energy market with large shares of VRE. A model with a fine temporal and spatial resolution is applied to simulate the expected wholesale electricity market in Northern Europe under different scenarios for flexibility in the power demand. The Northern European market is of particular interest for two reasons: First, it will likely have the largest VRE share in the world the coming decades, and second, it consists of a thermally dominated power supply in the southern regions and a more flexible hydro dominated supply in the northern ones. This implies that the scarcely studied impacts of VRE integration on regulated hydro power are being addressed (c.f. Hirth (2015b)). Additional to the numerical results, we also present a thorough analysis of how different energy system assumptions influence the impact of DR.

2 DR potentials and price responsiveness studies

Different measures and methods for describing flexible electricity consumption have been used in the literature. An overview of key DR measurement and simulation approaches is provided in the work of Albadi and El-Saadany (2008) where the actual peak demand reduction and demand price elasticity/elasticity of substitution are presented as the measures to define the performance of DR programs. There are only a limited number of studies focusing on the price elasticity of demand in real time. Lijesen (2007) gives an overview of empirical results regarding electricity price elasticities and estimates elasticities in the area of -0.0014 and -0.0043 for Dutch household customers. For Norwegian households Ericson (2006) uses hourly panel data and finds the price elasticity to be -0.02, but shows higher elasticity values for specific pricing contracts and automation technologies. Again for Norway, Ericson and Halvorsen (2008) estimate households' demand elasticity resulting from hourly spot pricing to be -0.059.

Sæle and Grande (2011) present observed DR as a kW response per hour. Having focused on Norwegian households, the authors analyze the effect from utilizing smart metering, remote load control, new pricing methods and technology for observing peak hour usage. The observed flexibility was a 1 kW per hour response for the customers with standard electrical water heaters. The response was a result from steering electricity usage away from the predefined peak load periods (8:00-10:00 and 17:00-19:00). The level of DR of electricity consumers in the future energy system is generally hard to predict since estimates based on historical data will exclude the impacts of new smart appliances and systems. Therefore, the DR assumptions applied in the current study are rather based on estimates for the future DR potential calculated for different countries. Such estimates are provided by the IEA in the information paper "Empowering Customer Choice in Electricity Markets" (IEA 2011a) and the working paper "Impact of Smart Grid Technologies on Peak Load to 2050" (IEA 2011b). The estimates represent the percentage of peak load that can be moved from one period of the day to another. According to these studies there is a considerable DR potential to be harnessed, with the projections indicating that about 18 % of the peak load in the Nordic region, on average, may be moved to off-peak hours. The type of demand changes considered within the demand response potentials are based on IEA documents as well. Dynamic pricing is assumed to be adopted following the installation of smart meters (IEA 2011b) and a move from centrally coordinated demand-side management measures towards an individual (price responsive) customer choice will take place. We consider dynamic pricing/real time pricing to be the tools for achieving the projected demand response potential. Thus, the risk associated with strategic behavior by the consumers (e.g. as a consequence of adverse selection and moral hazard problems (Bushnell et al. (2009))) will be minimized.

The numbers presented in the IEA documents constitute relatively reliable estimates of the potential DR and are considered a most suitable input for the model to be used. The DR estimates provided in the IEA publications are therefore chosen as a basis for the scenarios investigated in this study. Still, the IEA numbers are regarded as uncertain, and two additional DR scenarios are therefore analyzed (see Section 3.3).

Alternative approaches for modeling DR for scenario purposes can, however, be found in the literature. Black and Strbac (2006) describe the electricity DR as strongly dependent on the degree of flexibility of conventional generation. In their study three scenarios with moderate, medium and high generation system flexibility are considered, where the amount of minimum stable generation defines each scenario. Savolainen and Svento (2012) use an energy system model with four technologies and different shares of customers on RTP while Finn and Fitzpatrick (2014) apply consumer differentiated scenarios to analyze the potential for implementing price based DR. Other estimates used for modeling DR in recent research have been: percentage of smart metering penetration and energy saving equipment (Capgemini 2008), level of integration of distributed generation, amount of dispatchable load and storage (Siano 2014), and the previously mentioned peak demand reduction (Sæle and Grande 2011) and demand elasticity (Lijesen 2007, Ericson 2006, Ericson and Halvorsen 2008).

3 Methodology - Model structure, data and scenarios

In this section we introduce the power system model Balmorel that was applied for the analysis and present the DR scenarios that were investigated.

3.1 The equilibrium model Balmorel

Balmorel is a comprehensive equilibrium model for the power system of Germany, the Netherlands, the UK and the Nordic countries. Most exogenous parameters like demand, capacities of the different generation technologies, transmission capacity and VRE availability are specified individually for each region or country. The model version applied provides a specifically detailed representation of the Nordic countries: Norway includes 15 regions, Sweden 4 regions, and Denmark 2 regions, while the rest of the modeled countries are modeled with one region each. Previous scientific contributions applying earlier versions of the Balmorel model include: Karlsson and Meibom (2008), Münster and Meibom (2011), Juul and Meibom (2012), Münster et al. (2012). As a benchmark, real data for the year 2012 for installed capacity, demand, IRE production, hydro inflow, transmission capacities, export balance and fuel- and carbon prices are applied for the model calibration[1]. Based on observed hourly spot prices and other market data the model is calibrated for the calendar year 2012. The calibration results confirm that the model has a good accuracy in predicting electricity prices and production levels on an hourly level for all modeled countries. The updated model offers a number of important features that enable detailed analysis of a power system with high shares of VRE and realistic modeling of existing and future market conditions. It includes a more sophisticated modeling of reservoir hydropower and pumped storage, limitations in thermal flexibility, and a high degree of detail in technologies, time and space. In order to study the future energy system a "most likely" Baseline 2020 scenario is defined, where the future annual consumption levels and investments in new generation and transmission capacity are determined exogenously based on energy market forecasts, transmission grid development plans and planned energy market investments.

The Balmorel model represents a linear partial equilibrium approach simulating generation, transmission and consumption of electricity under the assumption of competitive markets (see e.g. Ravn 2001, Ravn, Hindsberger et al. 2001). The model calculates the electricity generation per technology, time unit and region, maximizing a consumer's utility function minus the cost of electricity generation, transmission and distribution. Mathematically, this can be expressed by an objective function subject to a number of linear constraints:

$$max \left[\sum_{s\in S}\sum_{t\in T}\sum_{r\in R}\left\{D_{r,s,t}(d_{r,s,t}) - \left(\sum_{i\in I}K_i^P(g_{r,i,s,t}) + \sum_{A\in R,A\neq r}K_{a,r}^T\left(X_{s,t}^{(a,r)}\right) + K^D\sum_{i\in I}g_{r,i,s,t}\right)\right\}\right] \quad (\forall r,a,i,s,t) \qquad (1)$$

In the Baseline scenario, the total power demand is determined exogenously for each region. The hourly variation in power demand is set equal to the observed hourly consumption profiles in 2012, scaled

[1] The data sources for the 2012 calibration and the 2020 scenario are provided by request.

according to the total annual power demand of the year to be studied. An energy balance constraint ensures that power supply must equal demand in every time step:

$$\sum_{i \in I} g_{r,i,s,t} + \sum_{a \in R, a \neq r} \left(X_{s,t}^{(a,r)} - X_{s,t}^{(r,a)} \right) = d_{r,s,t} \quad (\forall r, a, i, s, t) \qquad (2)$$

The model includes costs and losses of electricity distribution within each region, with the assumption of no constraints on the electricity flow within a region. Hourly trade with third countries is determined exogenously, while the power exchange between regions is determined endogenously, with restrictions on transmission capacities between regions:

$$X_{s,t}^{(a,r)} \leq \bar{X}^{(a,r)} \; (r \neq a) \qquad (\forall r, a, s, t) \qquad (3)$$

The supply side consists of various generation technologies, with a specified fuel type, fuel efficiency, variable and fixed costs, heat/power combination factor (CHP units) as well as environmental characteristics for each technology. The maximum capacity level constraint for a specific generation technology is defined by

$$g_{r,i,s,t} \leq \bar{g}_{r,i} \qquad (\forall r, i, s, t) \qquad (4)$$

Each thermal technology type is divided into four groups, with different fuel efficiency levels and variable production costs, representing the cost of old, average, new and future power plants. Plant-specific costs related to thermal power plant cycling (i.e. power plant start up, shut down, or operating at sub-optimal levels) are not modeled directly since all thermal power technologies are represented on an aggregated level. Instead, a novel approach is applied, where average cycling costs are included on an aggregated level. The marginal costs of thermal power technologies (K_{TH}^{P}) are divided into direct costs (k_{TH}^{d}) (fuel, CO2 and other variable costs) and cycling costs (k_{TH}^{c}). When the power ramping of a technology group is high from one hour to the next, power plant cycling is more likely to occur and will increase the marginal costs of the technology group. The cycling costs are modeled piecewise linearly by letting each technology group be able to operate in J=3 different operating modes $g_{r,i_{TH},t}^{j}$ ($j = \{low, medium, high\}$) based on the cycling condition.

$$g_{r,i_{TH},\mathrm{s,t}} = \begin{cases} g^{low}_{r,i_{TH},\mathrm{t}} \\ g^{medium}_{r,i_{TH2},\mathrm{t}} \\ g^{high}_{r,i_{TH3},\mathrm{t}} \end{cases} \quad \text{where} \quad \sum_{j\in J} g^{j}_{r,i_{TH},\mathrm{t}} = g_{r,i_{TH}} \qquad (\forall r, i_{TH}, s, t, j) \tag{5}$$

In each operating mode the technology group will have different capability of ramping power up or down from one hour to the next, with increasing cycling cost for increasing ramping capability.

$$\underline{ramp}^{j}_{i_{TH}} \cdot \bar{g}_{r,i_{TH}} \leq g^{\mathrm{j}}_{r,i_{TH},\mathrm{s,t}} - g^{\mathrm{j}}_{r,i_{TH},\mathrm{s,t-1}} \leq \overline{ramp}^{j}_{i_{TH}} \cdot \bar{g}_{r,i_{TH}} \quad (\forall r, i_{TH}, s, t, j) \tag{6}$$

An increased need for ramping up or down from one hour to the next will then force the model to select a more expensive operating mode of the technology, and hence induce increasing cycling costs for increasing levels of ramping. The cycling costs (k^{c}_{TH}) for each technology group are determined partly on the basis of cycling costs reported in the literature (Kumar et al. 2012) and partly through a thorough model calibration for the base year 2012 against observed historical market data for prices and hourly changes in production levels. The resulting average cycling costs give a conservative approximation compared with numbers found in the literature, which could be explained by the omission of cycling costs for units modeled as must-run technologies (i.e., nuclear power, CHP and other thermal must-run technologies), for which seasonal minimum and maximum production levels are defined as

$$\underline{g}_{r,i,s} \leq g_{r,i,s,t} \leq \bar{g}_{r,i,s} \qquad (\forall r, i = \{i_{NUC}, i_{CHP}\}, s, t) \tag{7}$$

VRE sources (i_{VRE}) (wind, solar power and run-of-the-river hydropower) have exogenously given production profiles varying on an hourly level according to variations in wind speed, sun light intensity and water flow:

$$g_{r,i_{VRE},s,t} \leq \bar{g}_{r,i_{VRE},s,t} \quad (\forall r, i_{VRE}, s, t) \tag{8}$$

In situations of congestion, the model allows for solar and wind curtailment instead of generating negative prices. This is rationalized by the assumption that the stringency of the current renewable energy priority dispatch rules is gradually reduced across Europe as the share of VRE increases. (Note that in the presence of feed-in tariffs or other premium systems, there will only be solar and wind curtailment once the negative power price exceeds the tariff level. Due to high uncertainty about future tariff levels such premiums are not considered in this study, which may cause a moderate over-estimation of the price, and an under-estimation of VRE production, in situations with VRE curtailment).

For reservoir hydro, the power generation is also limited by a reservoir equation (Equation 9), stating that the hydro storage level in the end of time period *s* is equal to the hydro resource in the end of the previous time period plus the inflow minus the total hydropower production during time period *s*. In addition, there are minimum and maximum restrictions on the hydro reservoir storage level (Equation 10), the starting levels for the hydro reservoirs (Equation 11) and the seasonal restrictions on the water flow through the hydro turbines (Equation 12):

$$v_{r,s} \leq v_{r,s-1} + \omega_{r,s} - \sum_{t\in T} g_{r,i_{HY},s,t} \qquad (\forall r, i_{HY}, s, t) \tag{9}$$

$$\underline{v_r} \leq v_{r,s} \leq \bar{v_r} \qquad (\forall r, s) \tag{10}$$

$$\underline{v_{0r}} \leq v_{r,1} \leq \overline{v_{0r}} \qquad (\forall r) \tag{11}$$

$$\underline{g}_{r,i_{HY},s} \leq g_{r,i_{HY},s,t} \leq \bar{g}_{r,i_{HY},s} \qquad (\forall r, i_{HY}, s, t) \tag{12}$$

Pumped storage is included in the model by adding the following sections to Equations 2 and 9:

$$\sum_{i\in I} g_{r,i,s,t} + \sum_{A\in R, A\neq r} \left(X_{s,t}^{(A,r)} - X_{s,t}^{(r,A)} \right) = d_{r,s,t} + d_{r,s,t}^{pump} = d_{r,s,t}^{total} \tag{2.2}$$

$$v_{r,s} \leq v_{r,s-1} + (\omega_{r,s} + \omega_{r,s}^{pump}) - \sum_{t\in T} g_{r,i_{HY},s,t} = v_{r,s-1} + \omega_{r,s}^{total} - \sum_{t\in T} g_{r,i_{HY},s,t} \tag{9.2}$$

where $\omega_{r,s}^{pump}$ is the water amount (measured in energy-units) pumped back to the hydro reservoirs and $d_{r,t}^{pump}$ is the energy used for pumping in hour t, such that

$$\omega_{r,s}^{pump} = \eta^{pump} \cdot \sum_{t\in T} d_{r,s,t}^{pump} \qquad (\forall r, s, t) \tag{13}$$

η^{pump} is the assumed pumped storage energy efficiency, which is set to 75% in this study.

Finally, we have the non-negativity restrictions:

$X_{s,t}^{(a,r)}, g_{r,i,s,t}, g_{r,i_{TH},t}^{j}, d_{r,s,t}, d_{r,s,t}^{pump}, v_{r,s}, \omega_{r,s}, \omega_{r,s}^{pump} \geq 0 \qquad (\forall r, a, i, s, t, j)$

Market clearing-conditions are analyzed by applying two different modes of the model: i) a long-term (one year) optimization horizon where the total regulated hydro generation is allocated to specific weeks, and ii) a short-term (weekly) optimization horizon with an hourly time resolution where the weekly hydropower supply is allocated on an hourly basis.

3.2 Endogenous modeling of demand response

The market impacts of different levels of DR (load shifting) are analyzed by assuming that a certain share of the observed difference between the daily maximum and the average demand may be shifted from one hour to another on a diurnal basis. We include DR in the energy balance by adding the following section to Equation 2.2:

$$\sum_i g_{r,i,s,t} + \sum_{A \in R, A \neq r} \left(X_{s,t}^{(A,r)} - X_{s,t}^{(r,A)} \right) = d_{r,s,t}^{total} + \Delta d_{r,s,t}, \quad (\forall r, a, i, s, t) \qquad (14)$$

Where $\Delta d_{r,s,t}$ could have either positive or negative value, depending on whether there is an upwards or downwards shift in demand. Furthermore, limitations on maximum allowed shift in demand in day n and hour *h*, are included by adding the following constraint (note that each time step can be represented by the indexes (s,t), i.e., the week number and hour of the week, or by (n,h), i.e., the day number and hour of the day, such that $d_{r,h,n} = d_{r,s,t}$ for (s,t) ∈ (n, h)):

$$\left| \Delta d_{r,n,h} \right| \leq \left(d_{r,n}^{max} - \overline{d}_{r,n} \right) \cdot \gamma_r \qquad \left(\overline{d}_{r,n} = \frac{1}{H} \sum_H d_{r,n,h} \right) \qquad (\forall r, n, h) \qquad (15)$$

where $d_{r,n,h}$ is the Baseline demand in region r, day n and hour *h*, $\overline{d}_{r,n}$ is the diurnal average electricity demand for region r in day *n* and γ is the assumed potential for demand shifting in region r, in percentage (see Section 3.3). Since this study only focuses on short-term shifts in demand, keeping the total daily demand constant, we also add the following constraint:

$$\sum_H \Delta d_{r,n,h} = 0 \quad \text{or, analogously:} \quad \sum_H \Delta \mathrm{d}_{r,n,h}^{up} = -\sum_H \Delta \mathrm{d}_{r,n,h}^{down} \qquad (\forall r, n, h) \qquad (16)$$

This constraint states that the sum of all shifted power within a day equals zero, consistent with only short-term changes.

3.3 Demand response scenarios

The system optimal demand response is determined endogenously based on the potential studies reported in Section 2. Three different DR scenarios are developed and compared to a Baseline scenario where today's level of DR is assumed: i) a Moderate DR scenario, where a 50 % realization of the maximum potential found in the IEA (2011) publications is assumed ii) a Full DR scenario where the maximum potential found in IEA (2011) is assumed implemented and iii) a High DR scenario, where we assume that strong policy measures are combined with technological developments such that the DR potential is doubled relative to the Full flexibility scenario. Table 1 reports the scenario assumptions that have been investigated (i.e., the DR levels (γ) for all modeled countries).

Table 1. Overview of the DR potential (γ) for each scenario. The potential is given in proportion (percentage) of the peak demand (defined as the demand exceeding the average consumption level) that can be shifted on a diurnal basis.

Flexibility scenario	DK	FI	NO	SE	GE	UK	NE
Baseline	-	-	-	-	-	-	-
Moderate response	4.0 %	10 %	12 %	7.5 %	6.0 %	6.0 %	6.0 %
Full response	8.0 %	19 %	24 %	15 %	12 %	12 %	12 %
High response	16 %	38 %	48 %	30 %	24 %	24 %	24 %

4 Results and discussion

The results chapter summarizes the most important numerical findings of the scenario analysis. In the first section, the Baseline scenario is presented, and the changes in production mix and consumption profiles when DR is introduced are analyzed. The second section investigates the influence of DR on the costs of electricity in terms of changes in electricity prices, consumers' costs and system costs. In the third section, we focus on the changes in profit for the different power technologies when introducing DR. The possible role of DR for VRE integration is investigated further in Section 4 by analyzing the changes in the residual demand (RD) level. Finally, in the end of Section 4 we provide two illustrative examples of how DR could improve the integration of VRE. Throughout the results chapter we mainly report for two representative countries: Norway, with a large share of regulated hydropower and hence a high degree of balancing capacity on the supply side, and Germany, with a large share of VRE and a relatively limited degree of flexibility on the supply side. If something else is not specified, we compare the Baseline and Full flexibility scenarios.

4.1 Production mix and consumption

In line with expectations regarding the transition to a low carbon energy system, a future Northern European power system with an almost 50% share of renewable energy sources is assumed for the simulations. Thermal power plants are, however, assumed to still take a significant part of the production mix, and about 30% of the total power production is expected to be coal and lignite power generation. With the assumed development in fuel prices, natural gas will mainly be used for peak production units (Figure 1), covering about 10% of the total electricity generation. Among the conventional energy sources natural gas and regulated hydropower will have the largest daily variations in generation volume (mid-merit plants), while lignite, nuclear power, biomass and CHP units will still function as base load power.

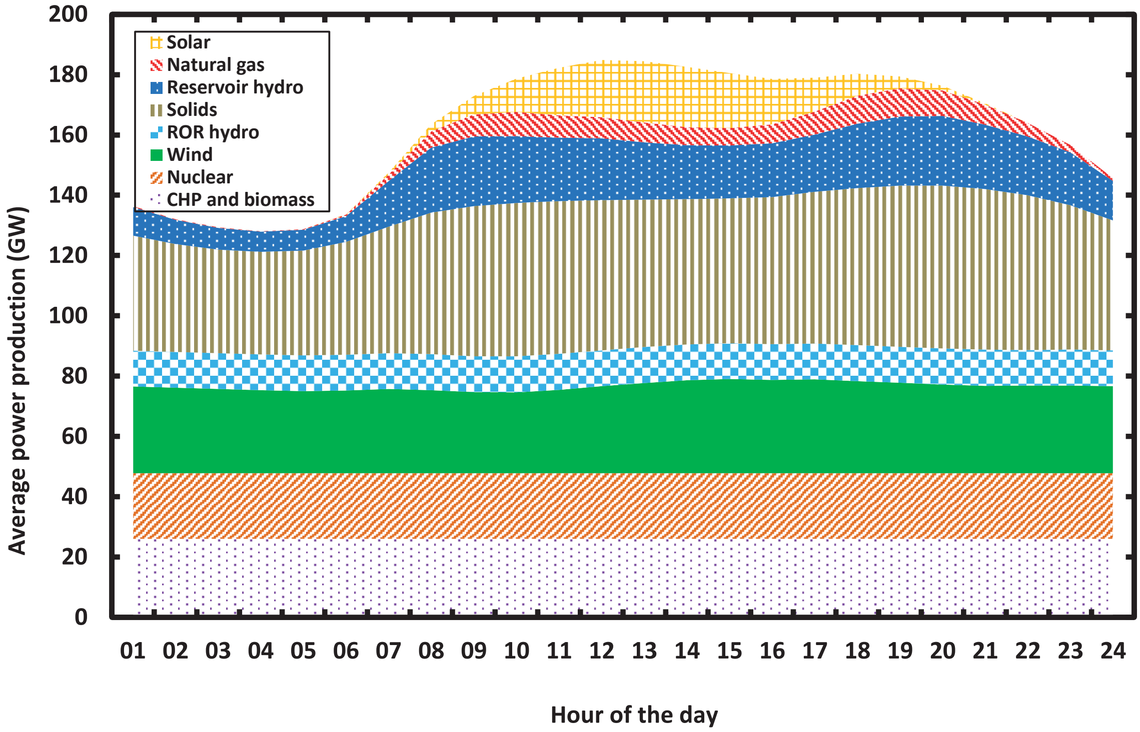

Figure 1. Northern European average diurnal production in the Baseline scenario (no flexibility). All-year average, all modeled countries.

When assuming increased DR (Figure 2) there is a general trend of reduced production from mid-merit technologies (natural gas, reservoir hydro and pumped hydropower), while coal and lignite power production is increased (Table 2). During peak hours, power generation from natural gas and coal is substantially reduced, but due to increased production in off-peak periods the total coal power generation increases with increased DR. This causes a 0.6 Mton increase in total GHG emissions (Full flexibility scenario). The mid-merit technologies (reservoir hydro, pumped hydro and natural gas) which are providing supply side flexibility have reduced daytime and increased nighttime generation when introducing DR. DR reduces VRE curtailment, causing a 0.7 TWh increase in annual power generation from VRE (Full flexibility scenario). The increased VRE production is caused partly by increased wind and ROR power generation in off-peak hours, due to fewer hours with excess power supply, and partly by increased solar power generation in peak hours.

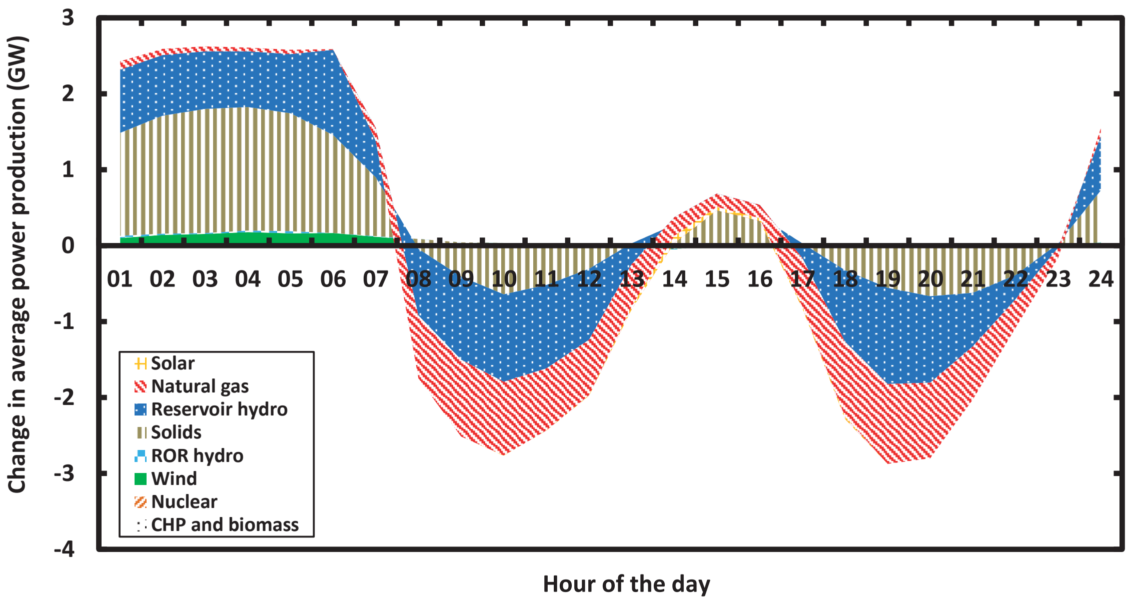

Figure 2. Change in the diurnal Northern European production mix caused by DR, Full flexibility scenario (all modeled countries, all-year average).

Table 2. Average production levels in the Baseline scenario and change in production for the different DR scenarios, total for all modeled countries and for Germany and Norway.

		Baseline scenario (total production in TWh)	DR scenarios (change in GWh)		
			Moderate	Full	High
Total	CHP, biomass and nuclear	**433**	-3	-40	-121
	Natural gas	**41**	-1996	-3775	-6941
	Coal and lignite	**403**	+1328	+2533	+4747
	Reservoir hydro and pumped storage	**146**	-613	-1162	-2079
	ROR hydro	**104**	+44	+67	+97
	Wind	**253**	+217	+501	+995
	Solar	**56**	+85	+101	+131
Germany	CHP, biomass and nuclear	**160**	+29	+24	+19
	Natural gas	**1.6**	-256	-459	-796
	Coal and lignite	**231**	+326	+635	+1234
	Reservoir hydro and pumped storage	**9.0**	-579	-1103	-1985
	ROR hydro	**20**	+13	+28	+42
	Wind	**113**	+54	+159	+338
	Solar	**50**	+70	+82	+106
Norway	CHP, biomass and nuclear	**0.6**	-	-	-
	Natural gas	**0.02**	-7	-11	-15
	Reservoir hydro and pumped storage	**86**	-31	-54	-86
	ROR hydro	**49**	+3	+6	+15
	Wind	**7.6**	+0.5	+0.7	+1.4

Figures 3.1 and 3.2 show the modeled average diurnal consumption profiles for all DR scenarios for Norway and Germany. For Norway, we observe a shift in the hourly demand from peak demand daytime hours to low demand nighttime hours, both for the summer and winter seasons. For Germany, the impacts are found to be different for different seasons. During winter weeks, the pattern is similar to the Norwegian one, with shifts in demand from peak hours to low demand night hours. During the summer season, on the other hand, increased DR cause increased consumption in the high demand daytime hours between 1 and 6 p.m. (Figure 3.3). This is explained by the peaking supply of solar power on mid-day hours, causing low residual demand levels and hence low prices. The interaction between DR and VRE is discussed further in Section 4.4.

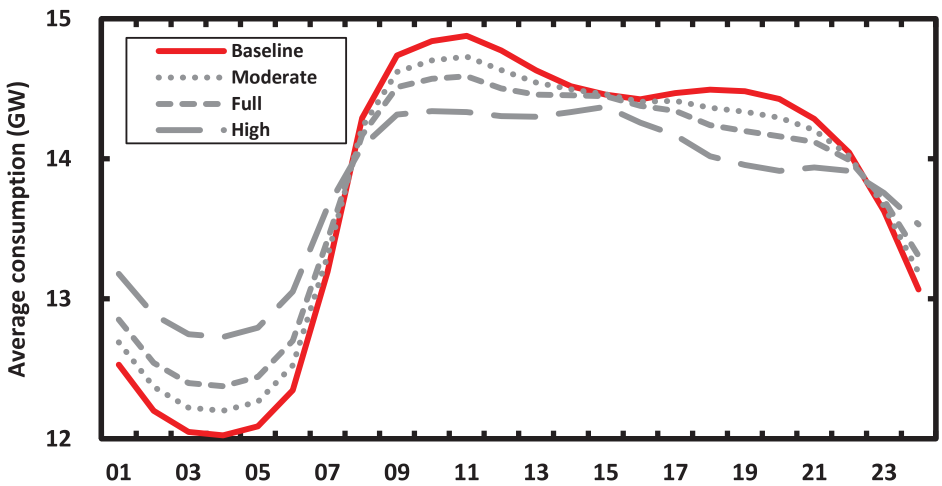

Fig. 3.1. Norway, all-year

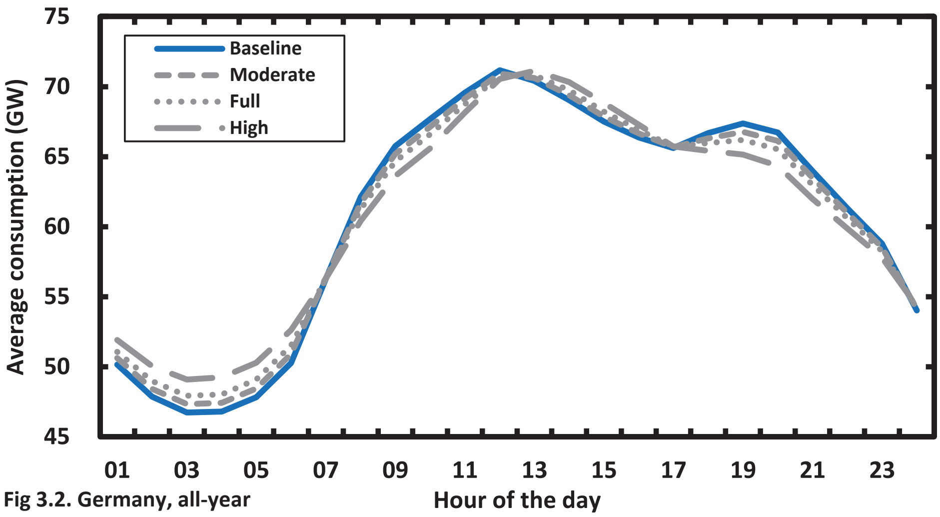

Fig 3.2. Germany, all-year

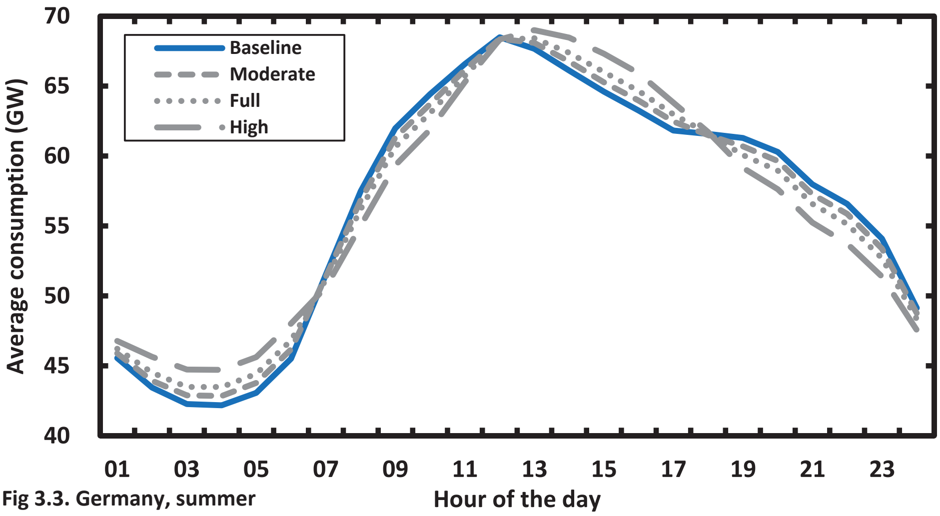

Fig 3.3. Germany, summer

Figure 3.1-3. Hourly variation of the daily electricity consumption for all DR scenarios, on an all-year basis (Norway and Germany) and for summer weeks (Germany) (note varying scale on the y-axis).

4.2 Prices and costs

The impacts of increased DR on the average electricity price levels are found to be low (Table 3). Also, the consumers' costs of electricity decrease moderately (0.2-0.8%). The small changes in the price level support the argumentation of Hirth (2015) that introducing DR will "pivot the marginal value curve clockwise" without affecting the electricity price level much. Nevertheless, the influence on the daily price profiles from DR is found to be considerable; the average intra-day price variation (defined as the standard deviation of the price within a day) is reduced by 12-22% for all countries. In the thermal power based countries the average daily maximum price also decreases by 3-3.7%. As expected, a more significant reduction in maximum price is observed for the thermal power based countries than for the countries with high shares of regulated hydropower.

Table 3. Average prices, daily maximum price and price variation in the Baseline scenario, and changes for the different DR scenarios.

	All results in (€/MWh)	Baseline scenario	DR scenarios: Moderate	DR scenarios: Full	DR scenarios: High	Percentage change (Full flexibility)
Germany	**Average prices**	**36.3**	-	+0.01	+0.05	+0.02 %
	Consumption weighted price	**37.8**	-0.1	-0.2	-0.3	-0.5 %
	Daily maximum price	**48**	-0.9	-1.6	-3.0	-3.40 %
	Intra-day price variation	**7.9**	-0.6	-1.1	-2.0	-13.8%
Norway	**Average prices**	**35.3**	+0.1	+0.18	+0.35	+0.50 %
	Consumption weighted price	**36.4**	+0.0	+0.1	+0.2	+0.2 %
	Daily maximum price	**38.8**	-0.4	-0.6	-1.0	-1.60 %
	Intra-day price variation	**2.7**	-0.3	-0.6	-1.0	-21.9%

There are seasonal differences in the price effects. While winter prices decrease moderately as the level of DR increases, summer prices are generally increasing. At summer nights the low demand level could often be covered by VRE and low priced base load power production, but due to an inelastic supply curve only small increases in power consumption may alter the market clearing price considerably. On summer daytime, on the other hand, the price reductions are limited due to a more elastic supply curve at daytime market clearing quantities. The price increase from DR during summer is somewhat counterintuitive, but will likely be a general effect in energy markets with large shares of VRE causing many hours with excess supply, and hence zero or negative prices. Figures 4.1-4 depict average diurnal electricity prices for Norway and Germany for all DR scenarios. For Norway, introducing DR induces only small changes in the average peak prices, but the daily price profile is generally smoothed (Figure 4.1). In the summer weeks, however, the decreased demand during daytime hours caused by the DR has almost no influence on the prices, while the nighttime prices increase considerably causing a total increase in the average prices (Figure 4.3).

Germany has a higher short-term price variation than Norway due to a less dynamic supply side in the short run, and the reduction in intra-day price variation caused by DR is, not surprisingly, higher (Figure 4.2). In the summer weeks, there is a quite distinct price drop in the high demand daytime hours between 1 and 6 p.m. due to solar power generation (Figure 4.4). When DR is introduced, this price drop is less clear due to a shift in demand towards the hours with excess solar power production.

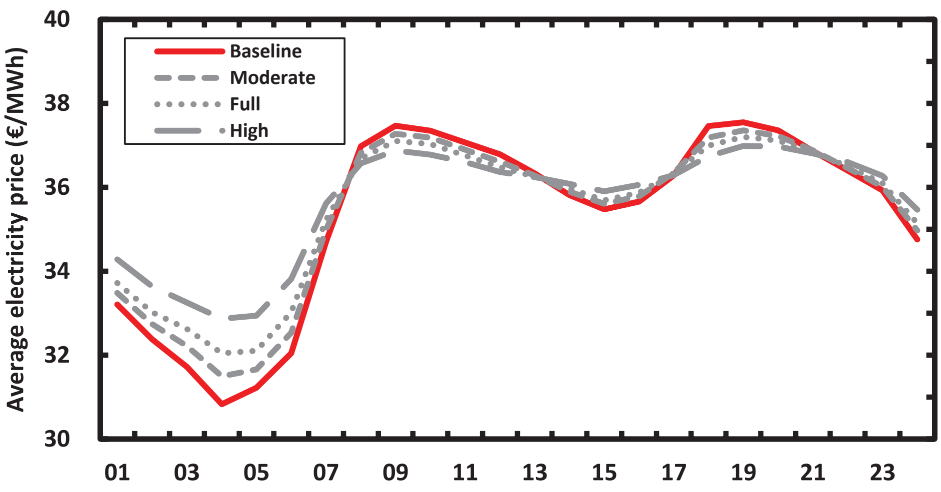

Fig 4.1. Norway, all-year

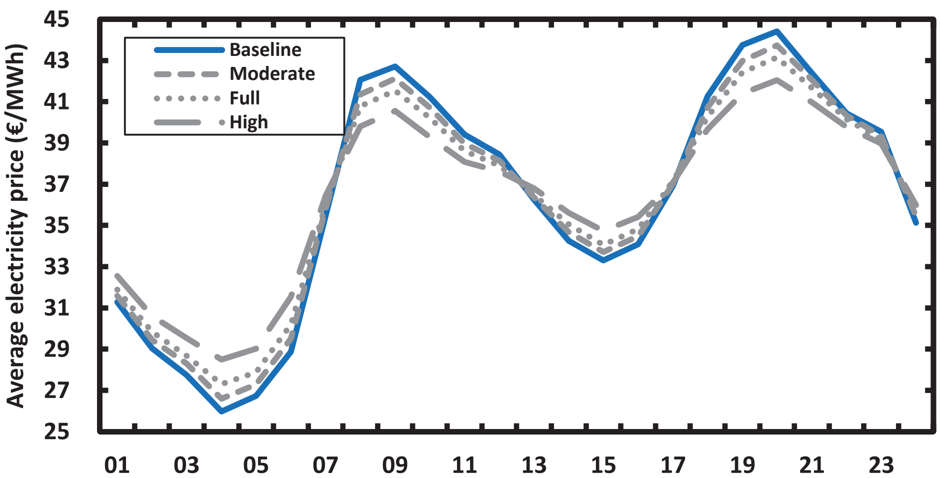

Fig 4.2. Germany, all-year

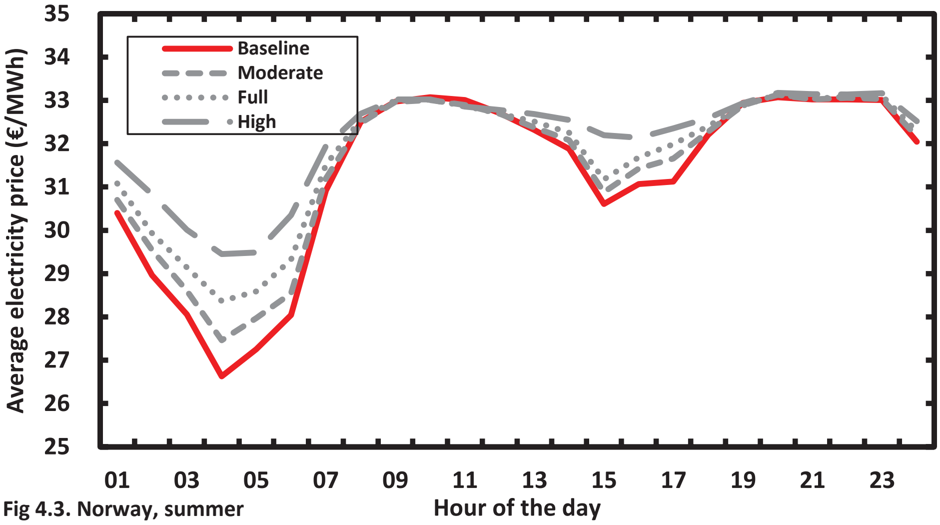

Fig 4.3. Norway, summer

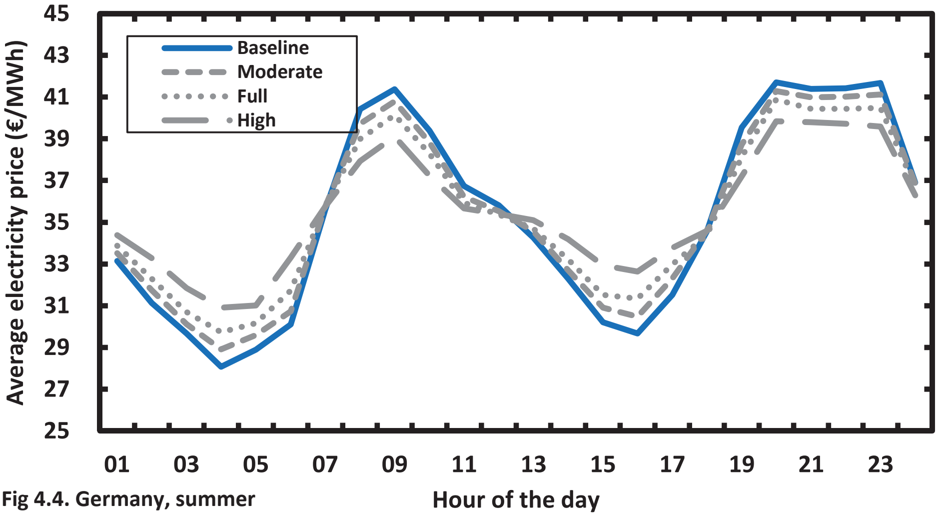

Fig 4.4. Germany, summer

Figure 4.1-4. Hourly intra-day variation of the electricity price for Norway and Germany (in €/MWh) and for all DR scenarios. (note varying scale on the y-axis).

The total consumers' cost of electricity is reduced slightly for all countries except Norway, with increased DR (Table 4). Summed up for all countries, we find a cost saving of 226 M€ for the consumers (Full flexibility scenario), which is only a 0.4% reduction of the total consumers' cost of electricity. A rough estimate of the cost savings for German households (assuming 40 million households holding a 30% share of the total electricity generation), suggests a very small annual saving per household of about 0.8 € per year. Furthermore, the model applied in this study does not reflect the capital expenditures associated with implementation of demand response activities. The quantification of such expenditures would require detailed data on the specific DR program, including both participant and system costs which, considering the diversity of enabling technologies, demand response initiatives and regulatory frameworks in the different countries, is hard to attain (Bradely et al. (2013)). To quantify the capital expenditures related to DR could be the aim of a separate study, such as the ones by the Department for Energy and Climate Change and Ofgem (2011a, 2011b) and Seebach et al. (2009). One estimate is provided by the study Smart Grid Economic and Environmental Benefits (Smart Grid Consumer Collaborative 2013), where the average cost of Smart Grid per customer is estimated to 284 Euro. Comparing this with the very limited benefits for the consumers, it is clear that policy instruments will be needed to enhance the level of price responsive demand modeled in this study.

Table 4. Changes in total annual system cost and consumers' costs, both total and for Norway and Germany.

	Baseline	Change in costs (M€)		
	scenario	Moderate	Full	High
Total consumers' costs in G€	**52.2**	**-124**	**-226**	**-354**
Norway	4.4	+4	+8	+19
Germany	20.1	-60	-109	-170

4.3 Producers' profit

The impacts of DR on producers' profit (income minus production costs) for the different power technologies are shown in Table 5. Reduced need for peak power production, together with reduced peak hour prices cause a significant decrease in the profit for natural gas and regulated hydropower producers. Due to increased demand in low demand nighttime hours, the profit for base load power producers is slightly increased when DR increases. Even though DR increases the total production from lignite and coal power plants, the profit decreases both on total and per-unit basis, since production is moved from high to low demand hours. Common for all the VRE production technologies is an increase in both total profit and profit per unit produced. DR is hence found to increase the market value of VRE, as suggested by Hirth

(2013). The reduced profit for some of the conventional technologies will likely accelerate scrapping of such capacity in the long run. This long run effect is not considered in this study.

Table 5. Profit from power production for the different technologies, measured in total annual profit and profit per produced unit

Profit		Baseline scenario	DR scenarios (change from Baseline)		
			Moderate	Full	High
Nuclear	total (G€, change in M€)	**5.1**	+7.2	+13.4	+28.3
	per unit produced (€/MWh)	**27.0**	+0.0	+0.1	+0.2
Natural gas	total (G€, change in M€)	**0.5**	-40.8	-74.8	-127.5
	per unit produced (€/MWh)	**11.5**	-0.5	-0.8	-1.4
Wind	total (G€, change in M€)	**8.3**	+24.6	+51.0	+95.5
	per unit produced (€/MWh)	**20.1**	+0.06	+0.12	+0.23
Coal and lignite	total (G€, change in M€)	**5.9**	-32.1	-58.7	-86.3
	per unit produced (€/MWh)	**14.8**	-0.1	-0.2	-0.4
ROR hydropower	total (G€, change in M€)	**3.5**	+10.7	+19.0	+36.5
	per unit produced (€/MWh)	**32.3**	+0.1	+0.2	+0.3
Reservoir hydropower	total (G€, change in M€)	**5.0**	-37.7	-70.9	-115.8
	per unit produced (€/MWh)	**34.1**	-0.1	-0.2	-0.3
Solar power	total (G€, change in M€)	**2.0**	+5.0	+10.2	+21.2
	per unit produced (€/MWh)	**30.7**	+0.08	+0.15	+0.32

4.4 System benefits and VRE integration

The observed changes in prices and production mix indicate that solutions for increased short-term DR could provide system benefits for the Northern European power sector in terms of decreased need for peak power technologies and reduced short-term price variation. To investigate further the possible role of DR for improved integration of large shares of VRE we analyze the changes in the residual demand (RD) level, defined as the total demand minus production from VRE ($RD_{r,s,t} = d_{r,s,t}^{total} + \Delta d_{r,s,t} - g_{r,i_{VRE},s,t}$). When introducing DR, the daily maximum RD is found to decrease by 2.6%, or almost 3.4 GW, on average (all countries) (Table 6). The maximum observed residual demand level on an annual basis is also reduced by more than 3.4 GW (all countries). For Germany alone, DR reduces the maximum RD by as much as 1.2

GW, and the average daily maximum by 1.3 GW. The reduced maximum RD suggests that DR will reduce the system's need for peak power technologies considerably.

Table 6. Maximum RD level on an annual basis for selected countries included in the analysis and for all countries

	Residual demand (GW)	Baseline scenario	DR scenarios (MW change)			Percentage change (Full flexibility)
			Moderate	Full	High	
All countries	Annual maximum	**205**	-1720	-3440	-6860	-1.7%
	Average daily maximum	**130**	-1690	-3360	-6620	-2.6%
Germany	Annual maximum	**80.3**	-610	-1210	-2420	-1.5%
	Average daily maximum	**53.8**	-650	-1290	-2580	-2.4%
Norway	Annual maximum	**18.8**	-210	-410	-660	-2.2%
	Average daily maximum	**8.8**	-160	-290	-480	-3.3%

To give two illustrative examples of how DR may improve the integration of VRE, a detailed representation of the market clearing conditions for selected weeks in Germany is provided in Figures 5 to 8. The graphs show market clearing conditions for a winter week (week 2) with varying wind power availability and relatively low solar power production (Figure 5 and Figure 6), and for a summer week (week 28) with high levels of solar power production and low wind power production (Figure 7 and Figure 8). For the winter week, consumption is generally shifted from high demand hours to low demand hours. When wind power availability is high in high demand hours the consumption is, however, also shifted to high demand hours (Figure 5), to some extent counteracting the prices from dropping to zero (Figure 6). In the summer weeks, when much solar power is available, demand is shifted to high demand hours due to high solar power production (Figure 7), here also counteracting drops in the electricity price (Figure 8).

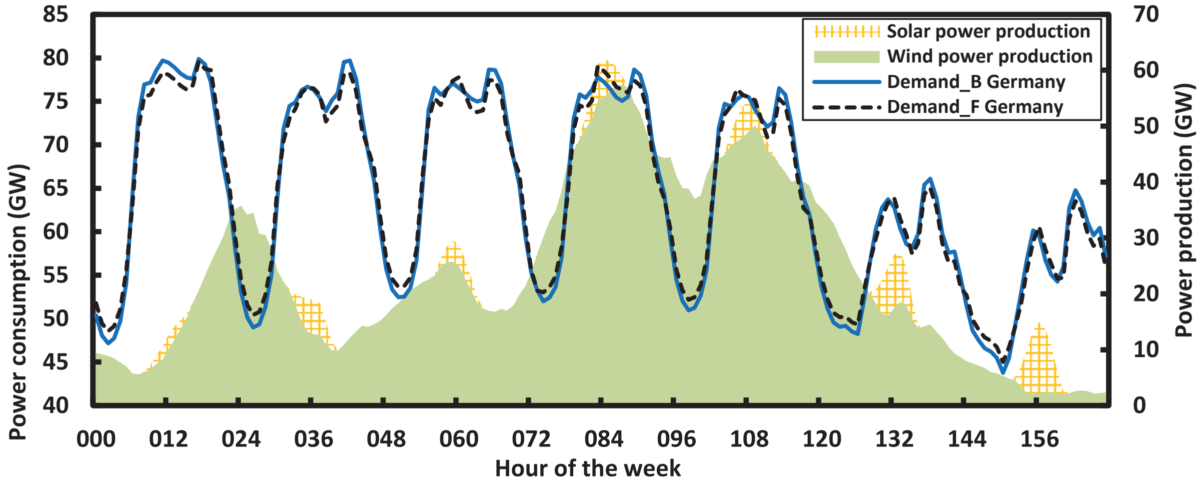

Figure 5. Left axis: Hourly power consumption for the Baseline and Full flexibility scenarios in week 2 of the year. Right axis: solar and wind power production. (note different scales on left and right axes)

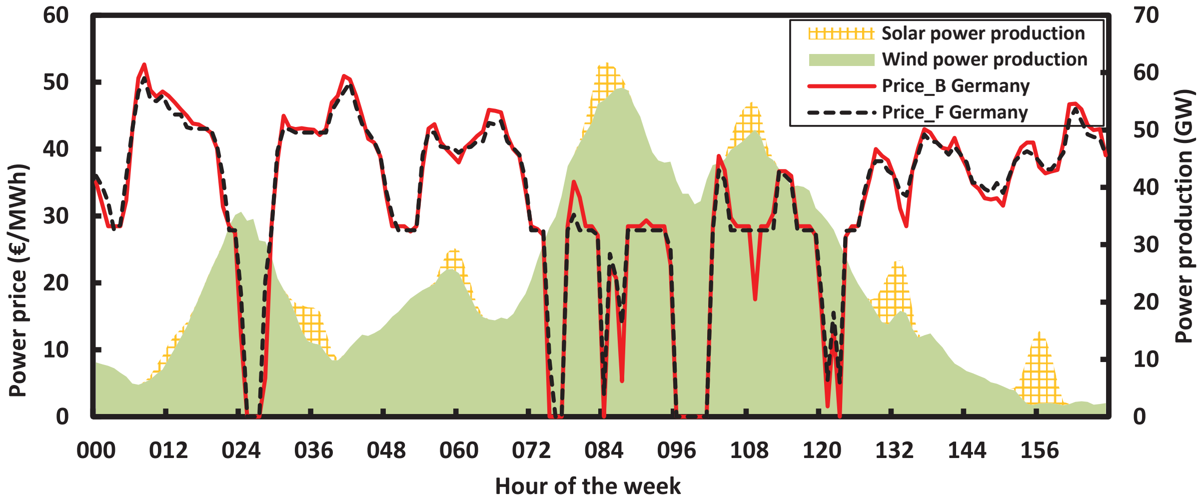

Figure 6. Left axis: Hourly power price for the Baseline and Full flexibility scenarios in week 2. Right axis: solar and wind power production.

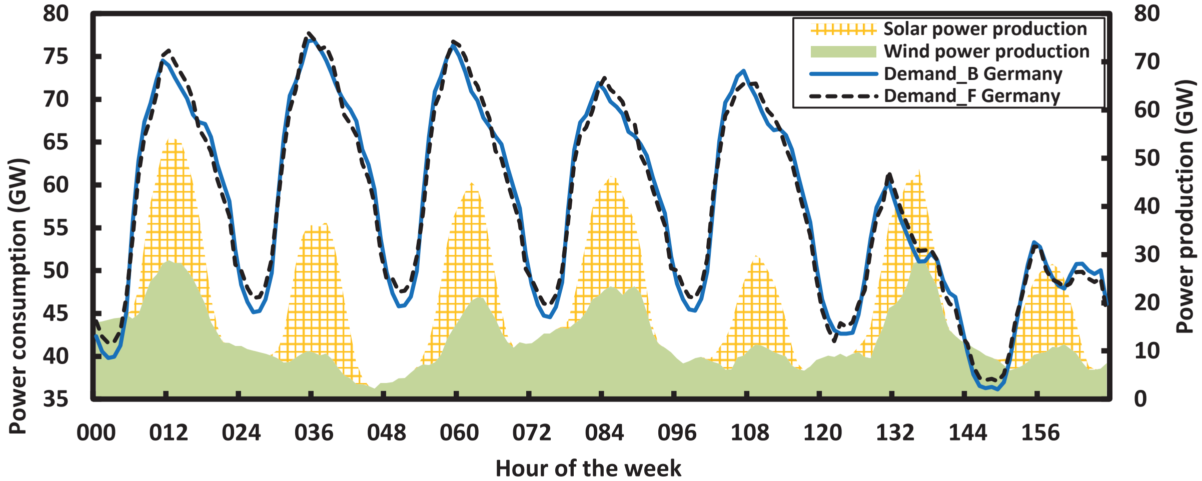

Figure7. Left axis: Hourly power consumption for the Baseline and Full flexibility scenarios in week 28. Right axis: solar and wind power production. (note different scales on left and right axes).

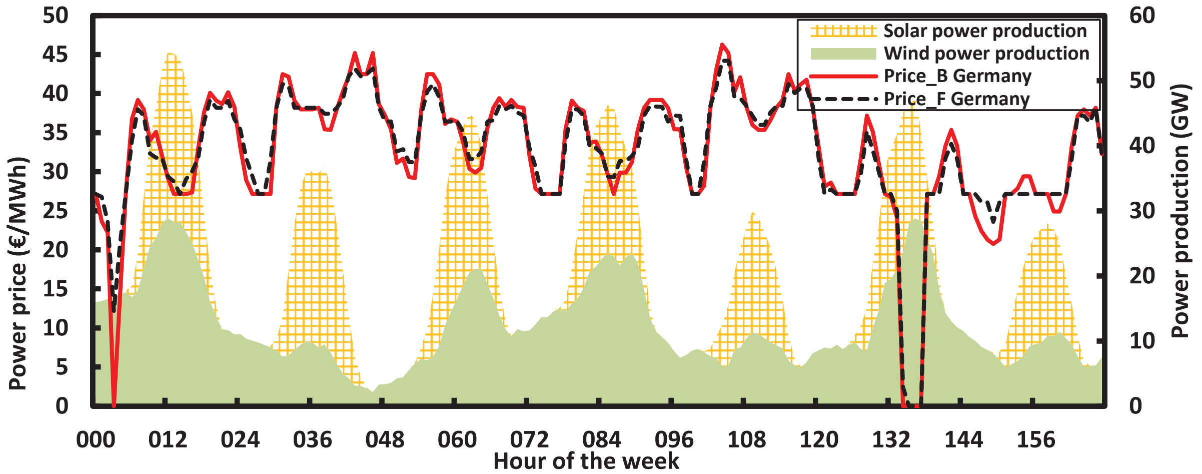

Figure 8. Left axis: Hourly power price for the Baseline and Full flexibility scenarios in week 28. Right axis: solar and wind power production.

5 Alternative market assumptions

In this section we investigate how the impact of DR depends on the future development of the power market by flexing the following important power market assumptions: A) the power consumption level (±20%), B) the VRE power generation level (±50%), C) the level of nuclear power generation (no nuclear/2012-level), D) the fuel price level (±50%) and E) the carbon price level (0-60 €/ton). Doing this we are also able to test how robust the most important conclusions are to changing model assumptions.

Below we report the general findings from these analyses, followed by a more thorough analysis of some key findings: i) the reduction in VRE curtailment, ii) the reduction in intra-day price variation, iii) the increased profit for VRE producers and iv) the change in total GHG emissions. Prices, costs, VRE production and RD are reported only for Germany, while producers' profit and GHG emissions are reported on system level. The numerical results from these sensitivity studies are reported in the Appendix.

General findings. By varying the power market assumptions A) to E) we find that the low impact of DR on the average power prices is robust to the assumptions analyzed (between 0-1.7%). Only small changes in the reduced annual (1.2-1.4 GW) and daily (1.2-1.3 GW) maximum RD from DR are found. By implementing the DR level assumed in this study, the annual and daily maximum RD is therefore expected to be considerably reduced, independent of how the power system develops in the future with respect to the assumptions A) to E). Also, reduced profit with DR for thermal and regulated hydropower production units is generally true for all underlying assumptions. Two exceptions are: i) profit for reservoir hydro increases with DR for high carbon prices, and ii) profit for coal and lignite increases with DR for low fuel price or VRE generation levels. As expected, DR is found to reduce the consumers' costs for all scenarios, but to varying degree (50-1050 M€). The assumption that is found to cause the highest reduction in consumers' costs is a high total power consumption level (A). By assuming a 20% higher consumption relative to the baseline scenario, DR will cause a 2.5% (1050 M€) reduction in annual consumers' costs (Full flexibility scenario), compared to only a 0.5% (110 M€) reduction in the Baseline scenario. DR is also found to reduce consumers' costs more when there is no nuclear power production (0.9% reduction), or when the fuel prices are high (0.6% reduction). This signals that DR is more advantageous for the consumers in supply-demand situations with high residual demand levels, or when high fuel prices cause very high peak prices. Compared to the effect of high fuel price levels, increasing the carbon price will have an opposite effect on the change in consumers' costs associated with DR. A high carbon price will increase the price of carbon-intensive base load technologies more than the peak production technologies and reduce the consumers' cost savings from DR. The assumed VRE level is not found to influence the consumers' savings from DR monotonically. Although the percentage reduction in consumers' costs from DR is higher for high VRE levels, the consumers' savings from DR are still higher in absolute values for low VRE production levels, since the residual demand levels are higher when VRE levels are low.

Reduced VRE curtailment. DR is found to reduce VRE curtailment independent of the underlying assumptions. The isolated effect of DR for reducing VRE curtailment is found to be highest when the RD level is low (i.e. a low consumption (A), high VRE (B) or high nuclear power production level (C)). In these situations there are more hours with excess VRE, and DR will hence more efficiently prevent VRE curtailment. The highest level of total VRE production is however obtained when DR is combined with a high RD level (a high consumption or a low nuclear power production level), a high fuel price level (D) or a high carbon price level (E). The synergy found between DR and the carbon price level for reducing VRE curtailment supports the finding of Savolainen and Svento (2012), who show that DR in the form of RTP is positively correlated with the carbon price for promoting market access for VRE.

Reduced short-term price variation. We have previously argued that a reduction in the intra-day variation of the electricity price as a consequence of reduced variations in the residual demand shows that DR will reduce the costs of VRE integration. The short-term variation in market clearing price is found to decrease significantly (between 10.6-15.3%) with DR, independent of the underlying assumptions. The degree to which DR reduces the price variation varies with the assumptions A) to E), as illustrated in Figure 9. Some findings are not very surprising: DR is expected to be more efficient for abating price variations if high consumption levels (A) or high fuel prices (D) cause very high peak hour prices. The same applies when the availability of nuclear base load production (C) is reduced. A tighter supply and demand balance causes market clearing prices that are generally more sensitive to variations in VRE generation, and DR could also more efficiently reduce VRE induced peaks and drops in the market price. Perhaps more surprising is that higher levels of total VRE production (B) make DR more efficient for reducing price variation. For high levels of VRE there are more hours with power excess, and DR could reduce VRE-induced drops in the market clearing prices by preventing VRE curtailment. Similar as for VRE curtailment here we also find a synergy between DR and the carbon price (E): high carbon price levels make DR more efficient for reducing VRE-induced short-term price variation.

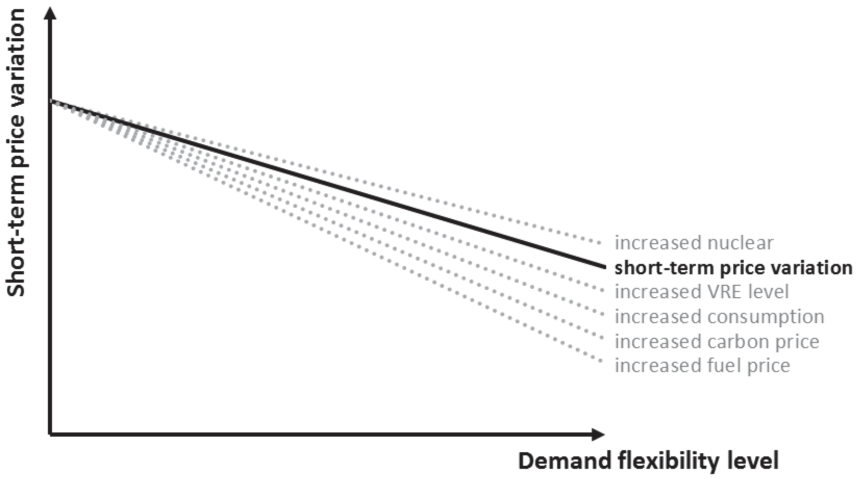

Figure 9. Short-term price variation as a function of DR level, and the influence of the power market assumptions A) to E).

VRE profit. The increase in VRE profit with DR is found to be more sensitive to the underlying assumptions (Figure 10). At high power consumption levels (A) VRE producers will generally receive a higher profit due to higher electricity prices, but since DR in this situation will cause a considerable decrease in peak prices, profit is decreased with DR for all production technologies, including VRE. Decreasing base load nuclear power generation (C) will have similar effect as an increase in the consumption level and is therefore also negatively correlated with the VRE profit from DR. For high levels of total VRE production (B) DR is found to increase VRE profit, while DR reduces VRE profit for low VRE production levels. For low VRE levels the positive correlation between VRE production and demand (i.e. more solar power production in high demand daytime hours) is stronger than the merit order effect (see Hirth (2013)), and introducing DR for low VRE levels will reduce this positive correlation, and hence the VRE profit. The carbon price (E) is found to be positively correlated with DR for increasing VRE profit, and the same applies for the fuel price levels (D). These results show that, for a future low-carbon energy system with a low power demand, increasing carbon price and a high share of VRE power generation, DR is likely to increase profit for VRE producers.

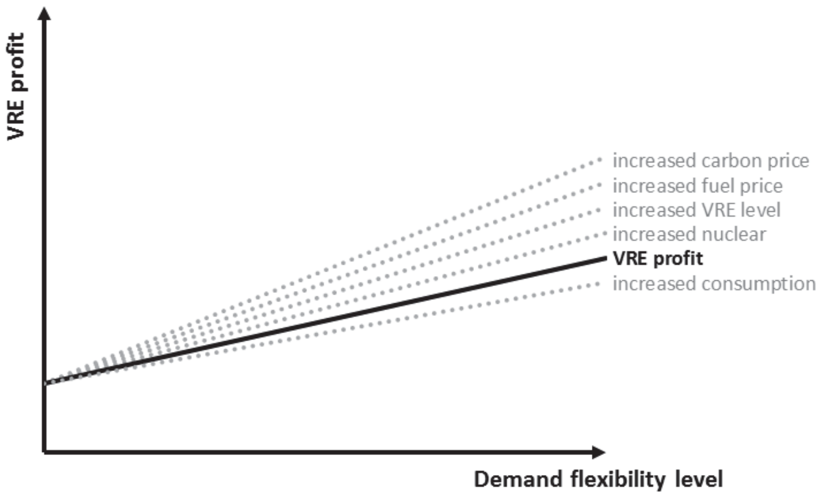

Figure 10. VRE profit as a function of DR level, and the influence of the underlying assumptions A) to E).

GHG emissions. The modeling results suggested that introducing DR will cause increased total GHG emissions caused by increased coal power generation in off-peak hours. We find, however, that the GHG effect of DR depends heavily on the future development of the parameters A) to E) (Figure 11). First, increased base load nuclear power production (C) or reduced power consumption level (A) will obviously prevent more coal and lignite to enter the market in off-peak hours and reduce the GHG emissions. Second, increased carbon price (E) will cause a fuel switch from high to lower carbon intensive technologies. Third, increasing levels of VRE production (B) combined with DR will imply less fossil based production, and hence have a positive effect on total GHG emissions. DR causes higher GHG emissions also in the high fuel price scenario, but the difference in emissions are lower than in the baseline case. In summary, the effect of DR on GHG emissions depends heavily on the underlying assumptions. To illustrate, if the carbon price continues to be low together with a decrease in nuclear power generation and an increased consumption level, the GHG emissions are expected to increase by implementing DR. If, on the other hand, the carbon price increases together with a low, or unchanged consumption level and increased VRE production level, implementing DR is likely to reduce GHG emissions.

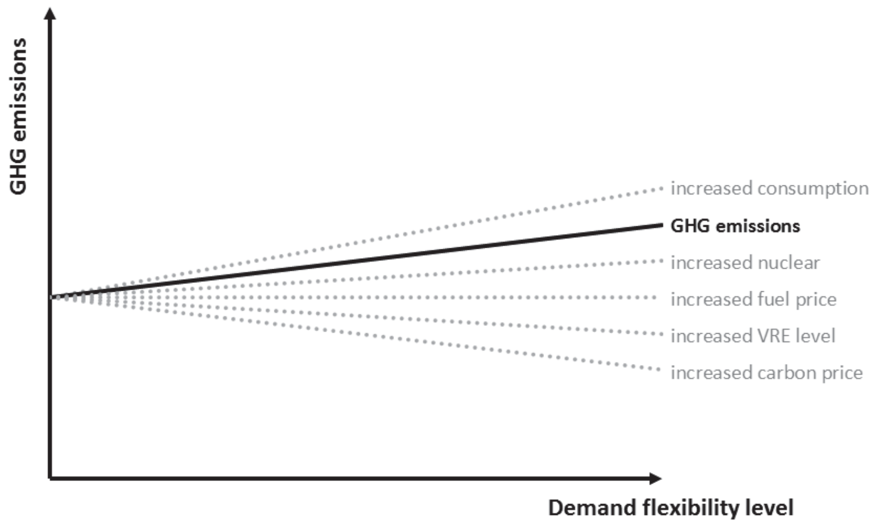

Figure 11. Change in GHG emissions as a function of DR level, and the influence of the underlying assumptions A) to E).

6 Scope and shortcomings of the modeling approach

In this chapter some of the strengths and weaknesses of the modeling approach will be discussed. First, the DR modeling approach applied in this study is compared with alternative approaches for modeling DR in energy systems with a high share of VRE. Second, we discuss the reliability of our results and the possible gains of applying a more detailed load flow model. Third, we justify the choice of a deterministic model and discuss the possible influence of DR on balancing costs.

In this study, the system optimal demand response is determined endogenously based on assumed DR potentials. By using prices and shifts in demand from the modeling results for Germany, we calculate the implied average price elasticities for the Moderate, Full and High flexibility scenario to -0.04, -0.08 and -0.21, respectively (note that these are average values, the elasticity will vary from hour to hour due to a different modeling approach). Interestingly, these implied elasticities are within the same range as in Savolainen and Svento (2012), who assume the following three elasticity levels, -0.025, -0.1 and -0.3, and Faruqui et al. (2009) who assume an elasticity of substitution between -0.05 and -0.08. To evaluate the suitability of different approaches for modeling DR for VRE integration, the change in RD is compared for the following three DR modelling approaches: (1) a system optimal demand response determined endogenously (this study's approach, Full flexibility scenario), (2) a demand response determined exogenously based on gross demand (Full flexibility scenario) and (3) an elasticity of substitution approach, as presented in Savolainen and Svento (2012), with an assumed price elasticity of -0.1 and a 0.666 share of consumers on RTP[2]. We find that the maximum residual demand level reduces substantially in all three cases, with a reduction of 1.2 GW (exogenous and endogenous modeling of DR) and 0.9 GW (elasticity of substitution). We see, however, that approach (1) and (3) are considerably more efficient in decreasing the daily variation in residual demand, with a 20% and 14% decrease, respectively, compared with a decrease of only 6% for approach (2). In a traditional thermal based power system, a monotonic shift in demand from high load day hours to low load night hours (i.e. approach (2)) would cause a system optimal demand profile. However, in a power system with large amounts of VRE, the present results illustrate the importance of consumers that are able to shift their demand according to changing levels of residual demand – and not only gross demand. The approach applied in this study is therefore considered a more realistic and appropriate representation of DR in a future energy system with a high share of VRE.

This study has an energy market approach and inter-regional congestion is not considered. The regionalization of the model has been chosen identical to the bidding areas defined by the TSOs in the real power market (apart from a higher detail level for Norway). Market splitting into bidding areas is an

[2] The following two simplifications were made: 1) The daily consumption-weighted average price was used as constant price to calculate the anchor point, and 2) to avoid unrealistically high peaks in demand in hours with very low prices we introduced a maximum shift in demand equal to the maximum shift in the endogenous and exogenous approaches.

important measure in the North-European market design for managing congestion and ensuring correct price signals. Congestion within a region is therefore assumed low and of less importance when studying the market effect of DR when shares of VRE are high. One should, however, mention that increasing shares of VRE also will cause further challenges for the TSOs in facilitating changing load flow situations. This will increase the need for power plant re-dispatch in the short-term, and demand grid investments and management of power plant location in the longer term (Frontier Economics and Consentec 2011). There is reason to believe that more system flexibility in the form of a more flexible power demand, with consequently reduced variation in RD, also could relieve congestion internally within a price area (see e.g., Kumar and Sekhar (2012); Liu et al. (2014); Yousefi et al. (2012)). By omitting inter-regional congestion, this study may therefore slightly underestimate the benefits of a more flexible power demand compared with a marginally more detailed load flow model. Notwithstanding, the influence of a more flexible demand on prices, production and transmission found from the model results are generally considered to be accurate, as inter-regional congestion is omitted in all model runs and will hence be underestimated by a similar amount for all scenarios.

The influence of DR on balancing costs is not directly quantified in this study, although the model results indicate that DR is likely to reduce the need for balancing reserves. The analysis is based on a deterministic model, with exogenous profiles for power demand, VRE generation and inflow to hydro reservoirs. In the real power market, combined forecasting errors in demand and conventional and variable power generation do cause an overall uncertainty in the balancing of demand and supply. Individual forecasting errors are generally not correlated, resulting in an overall smoothing effect when combined (Grubb 1991). Exemplified for Germany, day-ahead root-mean-square wind forecast errors (RMSE) for a single wind project is typically 10-15%, while the day-ahead wind forecast error for all of Germany is 5-7% (Ackermann 2005). Including stochastic modeling of VRE generation would be relevant for dealing with forecast errors and for analyzing the effect of DR on balancing costs. As argued by Hirth (2013), improved system flexibility, as DR is one example of, could reduce the balancing costs caused by VRE forecast errors. Omitting balancing costs in this study is therefore likely to underestimate the increased market value of VRE caused by DR. Furthermore, Siddiqui et al. (2000) show that the prices of ancillary services can be highly volatile under the presence of inelastic demand. This indicates that increased DR is not only expected to reduce the VRE induced fluctuations in market clearing prices, but in balancing prices and costs as well. The impact of changes in the electricity spot prices and in the volumes of regulating bids on the balancing prices in the Nordic region is analyzed by Ilieva and Bolkesjø (2014). Using the estimates on elasticity of the up- and down-regulating prices with respect to the electricity market price provided by Ilieva and Bolkesjø (2014) we calculate the changes in the balancing price as a consequence of the changes in the consumption weighted price we get when performing a sensitivity analysis in Section 5. The results indicate that there could be expected a maximum of 1.5 % reduction in the prices for up regulation and up to 1.4 % reduction in the prices for down regulation.

The model limitations discussed above suggest that the influence of DR found in this study should be regarded only as an approximation. However, all model studies have their limitations, and the general findings of the study are considered to be reliable. The possible benefits of including uncertainty in the modeling of VRE power generation would be achieved on the expense of other model qualities, since stochastic modeling comes with increased model complexity. The present study applies an energy market model that has a fine spatial and temporal resolution, which is advantageous in the modeling of DR effects. The choice of model is in line with the reasoning provided by e.g. Pina et al. (2011), Nelson et al. (2012) and Hirth (2013) who highlight the need for modeling tools with fine resolution in time and space when studying market and policy implication of energy systems with large VRE shares. The model is also well calibrated for the 2012 energy system in the regions analyzed and is improved for this study to include a better representation of the ramping restrictions on thermal plants, improved modeling of regulated hydropower supply and endogenous modeling of DR. Surprisingly, this is one of very few studies quantifying the impacts of increased DR on consumer's costs, producers' profit, VRE integration and on the energy system.

7 Conclusions

Using a power system model with fine spatial and temporal resolution, and IEA's estimates on demand response potentials, this study analyzes the market and system impacts of DR in a future Northern European energy market with large shares of VRE. The power price impact of increased DR varies over countries, seasons and time of day, but DR is generally found to have minor influence on the average electricity price. As a result, DR is only expected to cause moderate reductions in the consumers' cost of electricity (less than 1% cost reduction in most cases). Producers' profit is found to increase for all types and locations of VRE generation when DR increases, implying improved market value of VRE. Thermal power and reservoir hydropower producers will experience reduced profit with increasing DR. This implies that some of the increased flexibility provided on the demand side comes on the cost of less supply side flexibility. In the Baseline scenario, coal power production increases with increasing DR, causing increased GHG emissions. The GHG effect is, however, sensitive to assumptions regarding future fuel and carbon prices, consumption growth and generation capacity mix. Nevertheless, the GHG emission effects of increased DR can be questioned as long as coal power plants have a large share of the base load power. The study confirms that DR can provide system benefits, reducing the technical and economic challenges related to VRE integration. The short-term variation in prices and RD, as well as the daily maximum RD, is reduced considerably with increased DR, indicating reduced need for balancing reserves and reduced efforts to ensure capacity adequacy.

The effects of DR are generally found to be rather robust to different assumptions regarding the future power market. Independent of how the power system develops in the future, DR is expected to cause: i) a low impact on average power prices and consumers' costs of electricity, ii) a considerably reduced annual and daily maximum RD, iii) reduced VRE curtailment and iv) significantly reduced short-term price variation. DR will be more advantageous for the consumers in supply-demand situations with high residual demand levels, or when high fuel prices cause very high peak prices. A positive correlation is found between DR and the carbon price for reducing VRE curtailment, reducing VRE-induced short-term price variation and increasing VRE profit.

Although DR should not be regarded as the single solution, we conclude that DR is a promising option for integration of increasing shares of VRE. Yet, to effectively enhance VRE integration, consumers must shift their demand according to RD – and not only gross demand. Overall, the system benefits are found to be more important than the modest economic benefits for the consumers. Policies that stimulate increased flexibility on the consumer side will therefore be needed to fully utilize the system benefits and the potential for VRE integration from increased DR.

Acknowledgements

The authors would like to thank Bernt Bremdal, Thomas Martinsen, Steven A. Gabriel, the four anonymous referees as well as the Associate Editor for useful comments and discussions. The usual disclaimer applies.

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Appendix

Table A1. Numerical results of the sensitivity analysis presented in Chapter 5

	Baseline	Annual power consumption				VRE capacity		Nuclear power		Fuel price		High
All countries	scenario	-10 %	-20 %	+10 %	+20 %	-50 %	+50 %	low	high	low	high	carbon
Producers' revenues (G€)												
CHP, biomass and nuclear												
Baseline	15.6	10.8	7.9	19.8	34	21.5	9.7	14.5	15.8	9.2	28.3	22.4
Full flexibility	15.6	10.9	8	19.6	33.6	21.5	9.7	14.5	15.8	9.2	28.3	22.6
Change (M€)	**+13**	**+74**	**+14**	**-218**	**-320**	**-76**	**+18**	**-22**	**+28**	**+20**	**+6**	**+189**
Change (%)	**+0.1 %**	**+0.7 %**	**+0.2 %**	**-1.1 %**	**-0.9 %**	**-0.4 %**	**+0.2 %**	**-0.2 %**	**+0.2 %**	**+0.2 %**	**+0.0 %**	**+0.8 %**
Solids												
Baseline	17.3	11.8	7.8	24.3	34.8	27.5	11.2	20.8	15.8	9.5	32.2	12.2
Full flexibility	17.3	11.7	7.7	24.2	34.4	27.6	11.1	20.8	15.8	9.5	32.1	12.1
Change (M€)	**-2**	**-41**	**-119**	**-107**	**-476**	**+83**	**-100**	**-16**	**-2**	**+9**	**-57**	**-98**
Change (%)	**+0.0 %**	**-0.3 %**	**-1.5 %**	**-0.4 %**	**-1.4 %**	**+0.3 %**	**-0.9 %**	**-0.1 %**	**+0.0 %**	**+0.1 %**	**-0.2 %**	**-0.8 %**
Natural gas												
Baseline	2.2	1	0.4	5.3	13.9	5.3	1.5	3	2.1	1.7	4	10.4
Full flexibility	2.0	0.8	0.3	4.9	13.1	5.0	1.3	2.7	1.9	1.6	3.6	10.3
Change (M€)	**-245**	**-149**	**-88**	**-420**	**-802**	**-347**	**-193**	**-306**	**-226**	**-134**	**-434**	**-126**
Change (%)	**-10.9 %**	**-15.4 %**	**-23.9 %**	**-7.9 %**	**-5.8 %**	**-6.5 %**	**-12.8 %**	**-10.2 %**	**-10.8 %**	**-7.7 %**	**-10.9 %**	**-1.2 %**

All countries	Baseline scenario	Annual power consumption -10 %	-20 %	+10 %	+20 %	VRE capacity -50 %	+50 %	Nuclear power low	high	Fuel price low	high	High carbon
Reservoir hydro												
Baseline	5.5	2.8	1.8	4.6	7.3	2.7	2.6	6	5.3	3.2	9.9	5.2
Full flexibility	5.4	2.7	1.7	4.5	7.3	2.7	2.6	5.9	5.2	3.2	9.8	5.2
Change (M€)	**-86**	**-34**	**-60**	**-22**	**-46**	**-7**	**-40**	**-110**	**-72**	**-45**	**-150**	**+2**
Change (%)	**-1.6 %**	**-1.2 %**	**-3.3 %**	**-0.5 %**	**-0.6 %**	**-0.3 %**	**-1.5 %**	**-1.8 %**	**-1.4 %**	**-1.4 %**	**-1.5 %**	**+0.0 %**
Variable renewables												
Baseline	13.8	9.8	7.3	18	33.4	14.4	11.4	15.3	13.1	8.2	25.1	20.8
Full flexibility	13.9	9.9	7.3	17.7	33.0	14.2	11.5	15.4	13.2	8.2	25.3	21.1
Change (M€)	**+80**	**+131**	**+65**	**-257**	**-462**	**-177**	**+124**	**+65**	**+87**	**+56**	**+151**	**+293**
Change (%)	**+0.6 %**	**+1.3 %**	**+0.9 %**	**-1.4 %**	**-1.4 %**	**-1.2 %**	**+1.1 %**	**+0.4 %**	**+0.7 %**	**+0.7 %**	**+0.6 %**	**+1.4 %**
GHG emissions (Mton)												
Baseline	418	327.6	251	509.2	588.1	557.3	308	462.7	395.9	406	420.4	256.7
Full flexibility	418.7	327.4	249.3	510.2	588.8	559.0	306.9	463.6	396.5	406.6	420.9	256.1
Change	**+0.6**	**-0.2**	**-1.8**	**+0.9**	**+0.7**	**+1.7**	**-1.1**	**+0.9**	**+0.6**	**+0.6**	**+0.4**	**-0.6**
Change (%)	**+0.2 %**	**-0.1 %**	**-0.7 %**	**+0.2 %**	**+0.1 %**	**+0.3 %**	**-0.4 %**	**+0.2 %**	**+0.1 %**	**+0.2 %**	**+0.1 %**	**-0.2 %**

Germany	Baseline scenario	Annual power consumption				VRE capacity		Nuclear power		Fuel price		High carbon
		-10 %	-20 %	+10 %	+20 %	-50 %	+50 %	low	high	low	high	
Electricity price (€/MWh)												
Average price												
Baseline	36.3	28.4	21.8	44.8	61.5	48.7	25.3	42	33.6	21.6	65.5	50.6
Full flexibility	36.3	28.5	21.8	44.5	60.5	48.6	25.3	41.9	33.7	21.7	65.5	50.7
Change	**+0.0**	**+0.1**	**+0.0**	**-0.3**	**-1.0**	**-0.1**	**+0.0**	**-0.1**	**+0.0**	**+0.0**	**+0.0**	**+0.1**
Change (%)	**+0.0 %**	**+0.4 %**	**+0.0 %**	**-0.6 %**	**-1.7 %**	**-0.1 %**	**-0.1 %**	**-0.3 %**	**+0.1 %**	**+0.1 %**	**+0.0 %**	**+0.2 %**
Load weighted price												
Baseline	37.8	29.8	23	46.9	66.1	50.4	26.7	43.7	35.1	22.5	68.1	52.1
Full flexibility	37.5	29.7	22.8	46.3	64.4	50.1	26.5	43.3	34.9	22.4	67.8	52.0
Change	**-0.2**	**-0.1**	**-0.2**	**-0.6**	**-1.6**	**-0.3**	**-0.2**	**-0.4**	**-0.2**	**-0.1**	**-0.4**	**-0.1**
Change (%)	**-0.5 %**	**-0.3 %**	**-0.9 %**	**-1.3 %**	**-2.5 %**	**-0.6 %**	**-0.8 %**	**-0.9 %**	**-0.4 %**	**-0.4 %**	**-0.6 %**	**-0.2 %**
Price variation												
Baseline	12.3	12.3	12	16.8	40.5	10.7	15.8	13.5	12.3	6.9	22.9	12.9
Full flexibility	11.6	11.6	11.4	15.0	37.4	9.9	15.1	12.4	11.7	6.5	21.5	12.1
Change	**-0.7**	**-0.7**	**-0.6**	**-1.9**	**-3.1**	**-0.8**	**-0.6**	**-1.1**	**-0.6**	**-0.4**	**-1.4**	**-0.8**
Change (%)	**-5.9 %**	**-5.4 %**	**-4.9 %**	**-11.1 %**	**-7.7 %**	**-7.5 %**	**-4.1 %**	**-8.0 %**	**-5.1 %**	**-6.1 %**	**-6.1 %**	**-5.9 %**
Daily price variation												
Baseline	7.9	8.1	8.1	9.9	17.9	7.6	10.4	8.3	7.8	4.7	13.6	8.2
Full flexibility	6.8	7.0	7.0	8.4	15.4	6.6	9.3	7.1	6.8	4.1	11.7	7.0
Change	**-1.1**	**-1.1**	**-1.1**	**-1.5**	**-2.4**	**-0.9**	**-1.1**	**-1.2**	**-1.0**	**-0.6**	**-1.9**	**-1.1**
Change (%)	**-13.8 %**	**-13.6 %**	**-13.8 %**	**-15.3 %**	**-13.7 %**	**-12.5 %**	**-10.6 %**	**-14.7 %**	**-12.7 %**	**-13.5 %**	**-14.2 %**	**-13.6 %**

Germany	Baseline scenario	Annual power consumption -10 %	Annual power consumption -20 %	Annual power consumption +10 %	Annual power consumption +20 %	VRE capacity -50 %	VRE capacity +50 %	Nuclear power low	Nuclear power high	Fuel price low	Fuel price high	High carbon
Consumer's cost (G€, change in M€)												
Baseline	20.1	14.2	9.8	27.4	42.1	26.8	14.2	23.2	18.6	11.9	36.2	27.7
Full flexibility	20.0	14.2	9.7	27.1	41.1	26.6	14.1	23.0	18.6	11.9	36.0	27.6
Change	**-109**	**-48**	**-85**	**-344**	**-1044**	**-161**	**-118**	**-200**	**-80**	**-50**	**-200**	**-63**
Change (%)	**-0.5 %**	**-0.3 %**	**-0.9 %**	**-1.3 %**	**-2.5 %**	**-0.6 %**	**-0.8 %**	**-0.9 %**	**-0.4 %**	**-0.4 %**	**-0.6 %**	**-0.2 %**
Production from VRE (TWh)												
Baseline	182.4	182.2	180.3	183.2	183.5	92	262.9	183.4	181.7	182.4	182.5	182.7
Full flexibility	182.7	182.5	180.8	183.3	183.6	92.0	263.8	183.5	182.1	182.7	182.8	182.9
Change	**+269**	**+336**	**+476**	**+157**	**+81**	**+1**	**+913**	**+122**	**+438**	**+255**	**+278**	**+186**
Change (%)	**+0.1 %**	**+0.2 %**	**+0.3 %**	**+0.1 %**	**+0.0 %**	**+0.0 %**	**+0.3 %**	**+0.1 %**	**+0.2 %**	**+0.1 %**	**+0.2 %**	**+0.1 %**
Residual demand (GW)												
All-year average												
Baseline	40.0	33.9	28.0	46.0	52.0	50.3	30.7	39.8	40.0	40.0	39.9	39.9
Full flexibility	39.9	33.9	28.0	45.9	52.0	50.3	30.6	39.8	40.0	39.9	39.9	39.9
Change	**+0.0**	**+0.0**	**-0.1**	**+0.0**	**+0.0**	**+0.0**	**-0.1**	**+0.0**	**-0.1**	**+0.0**	**+0.0**	**+0.0**
Change (%)	**-0.1 %**	**-0.1 %**	**-0.2 %**	**+0.0 %**	**+0.0 %**	**+0.0 %**	**-0.3 %**	**+0.0 %**	**-0.1 %**	**-0.1 %**	**-0.1 %**	**-0.1 %**
Annual maximum												
Baseline	80.3	71.9	63.6	88.7	97.1	82.1	78.8	80.3	80.3	80.3	80.3	80.3
Full flexibility	79.1	70.7	62.3	87.5	95.9	80.9	77.5	79.1	79.1	79.1	79.1	79.1
Change	**-1.2**	**-1.2**	**-1.2**	**-1.2**	**-1.2**	**-1.2**	**-1.4**	**-1.2**	**-1.2**	**-1.2**	**-1.2**	**-1.2**
Change (%)	**-1.5 %**	**-1.7 %**	**-2.0 %**	**-1.4 %**	**-1.2 %**	**-1.5 %**	**-1.7 %**	**-1.5 %**	**-1.5 %**	**-1.5 %**	**-1.5 %**	**-1.5 %**

Germany	Baseline scenario	Annual power consumption				VRE capacity		Nuclear power		Fuel price		High carbon
		-10 %	-20 %	+10 %	+20 %	-50 %	+50 %	low	high	low	high	
Average daily maximum												
Baseline	53.8	47.2	40.6	60.5	67.2	60.7	47.8	53.8	53.8	53.8	53.8	53.8
Full flexibility	52.5	45.9	39.3	59.2	65.9	59.4	46.5	52.5	52.5	52.5	52.5	52.5
Change	**-1.3**	**-1.3**	**-1.3**	**-1.3**	**-1.3**	**-1.3**	**-1.2**	**-1.3**	**-1.3**	**-1.3**	**-1.3**	**-1.3**
Change (%)	**-2.4 %**	**-2.7 %**	**-3.1 %**	**-2.1 %**	**-1.9 %**	**-2.1 %**	**-2.6 %**	**-2.4 %**	**-2.4 %**	**-2.4 %**	**-2.4 %**	**-2.4 %**
Average daily variation												
Baseline	8.7	8.3	7.8	9.2	9.8	7.5	10.6	8.8	8.6	8.7	8.7	8.7
Full flexibility	7.8	7.4	7.0	8.3	8.8	6.6	9.9	7.9	7.7	7.8	7.8	7.8
Change	**-0.9**	**-0.9**	**-0.9**	**-0.9**	**-1.0**	**-0.9**	**-0.7**	**-0.9**	**-0.9**	**-0.9**	**-0.9**	**-0.9**
Change (%)	**-10.8 %**	**-11.0 %**	**-11.1 %**	**-10.3 %**	**-9.8 %**	**-12.6 %**	**-7.0 %**	**-10.7 %**	**-10.7 %**	**-10.7 %**	**-10.8 %**	**-10.8 %**