Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Ecology
and Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2015:56

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

Iliana Ilieva

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Ås 2015

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

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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.

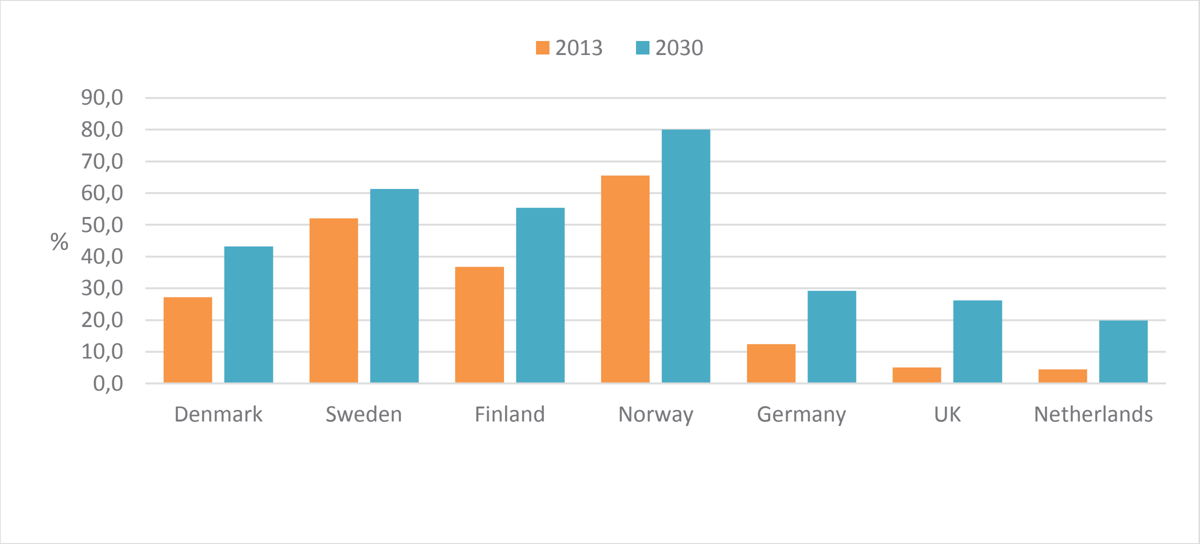

Figure 1 – Percentage share of renewable energy in the energy consumed: data for 2013 (Eurostat) and projections for 2030 based on the EC's 2030 targets and an assumption for growing energy demand as in the EC's Energy Roadmap 2050 (Bendiksen 2014; EC 2011a; Intelligent Energy Europe 2014)

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).

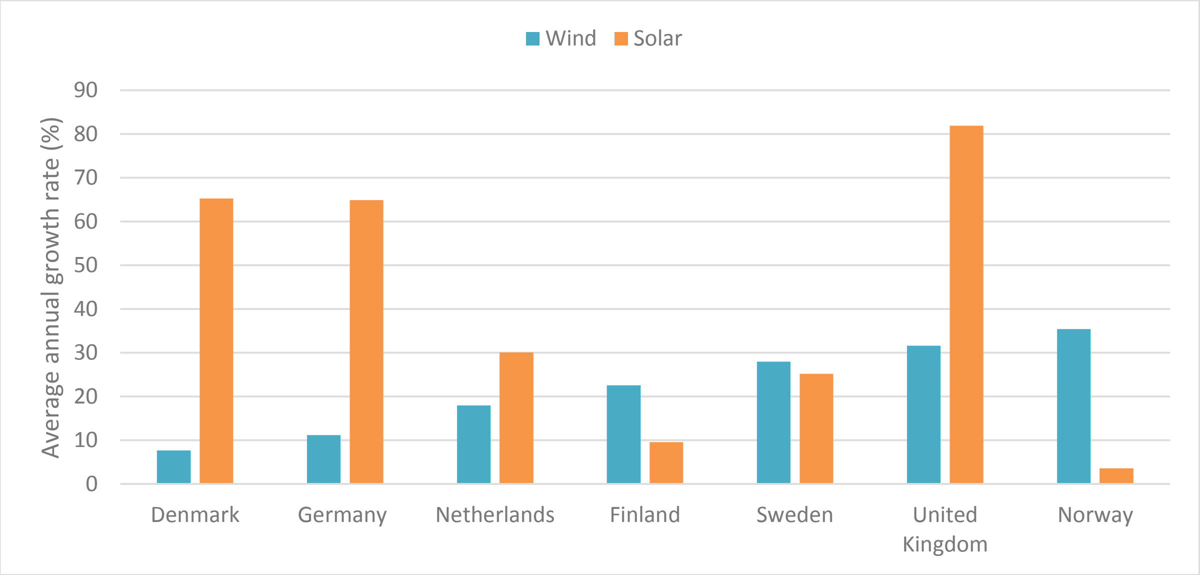

Figure 2 – Average annual growth rate for wind and solar power generation for the period 2002-2012
Data source: Worldwide electricity production from renewable energy sources, Fifteenth Inventory - Edition 2013; Statistics and figure series

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,

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[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

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[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

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[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.

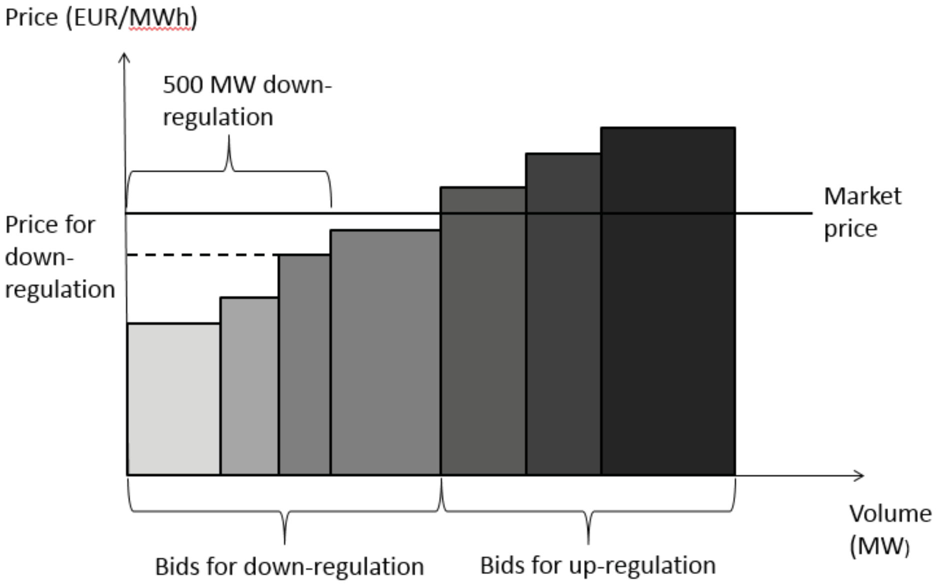

Figure 3 – Price setting in the balancing power market

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)

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

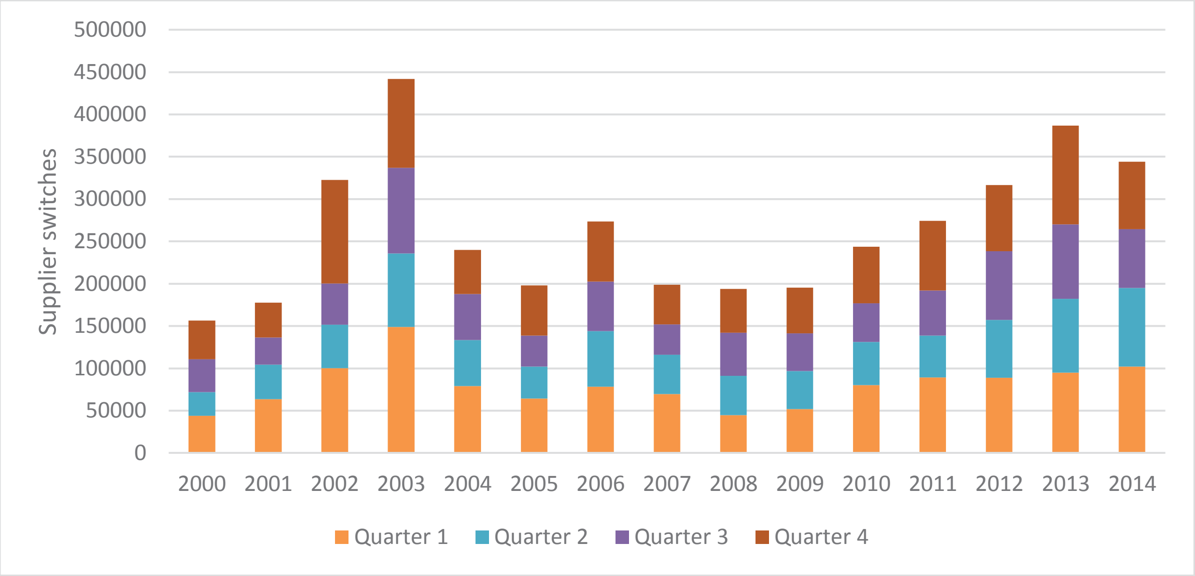

Figure 4 – Number of supplier switches in Norway for the period 2000-2014 (quarterly).
Data source: NVE

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.

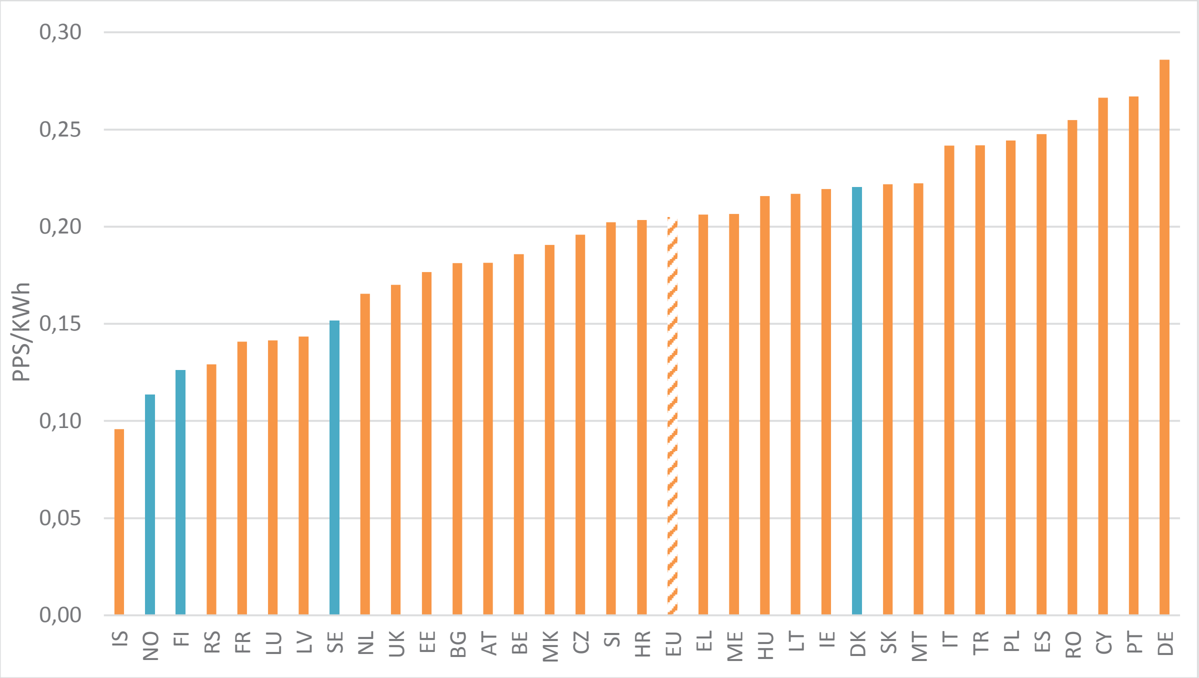

Figure 5 – Electricity prices for household customers in the European countries during 2014 (PPS/kWh)
Data source: Eurostat

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.

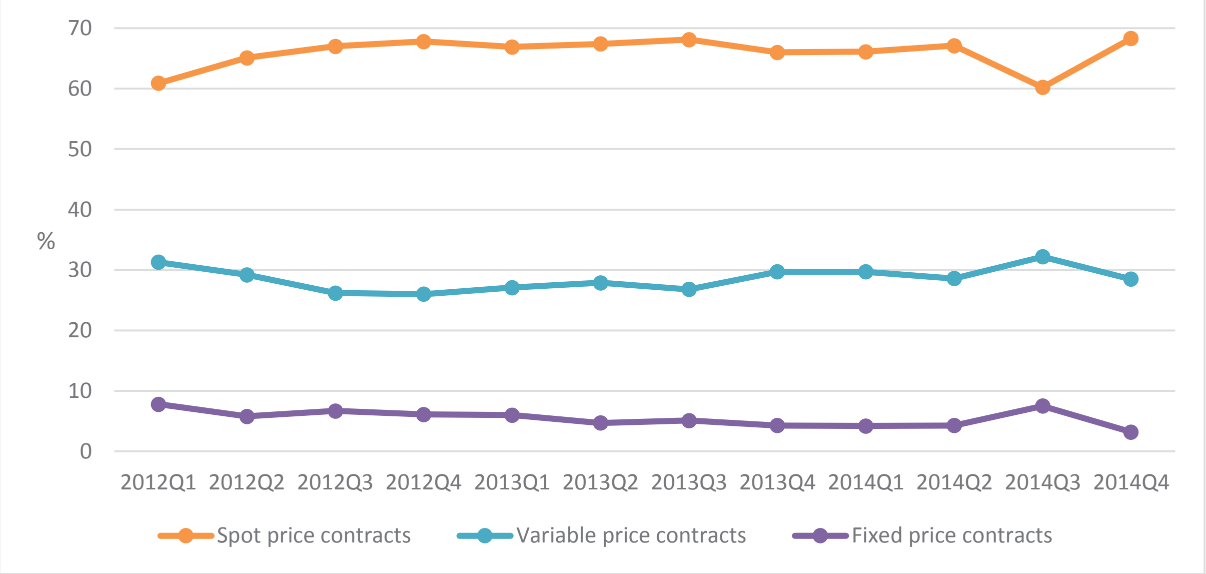

Figure 6 – Percentage share of retail contracts in the Norwegian end-user market. Quarterly data for 2012-2014.
Data Source: Statistics Norway

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

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[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

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[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.

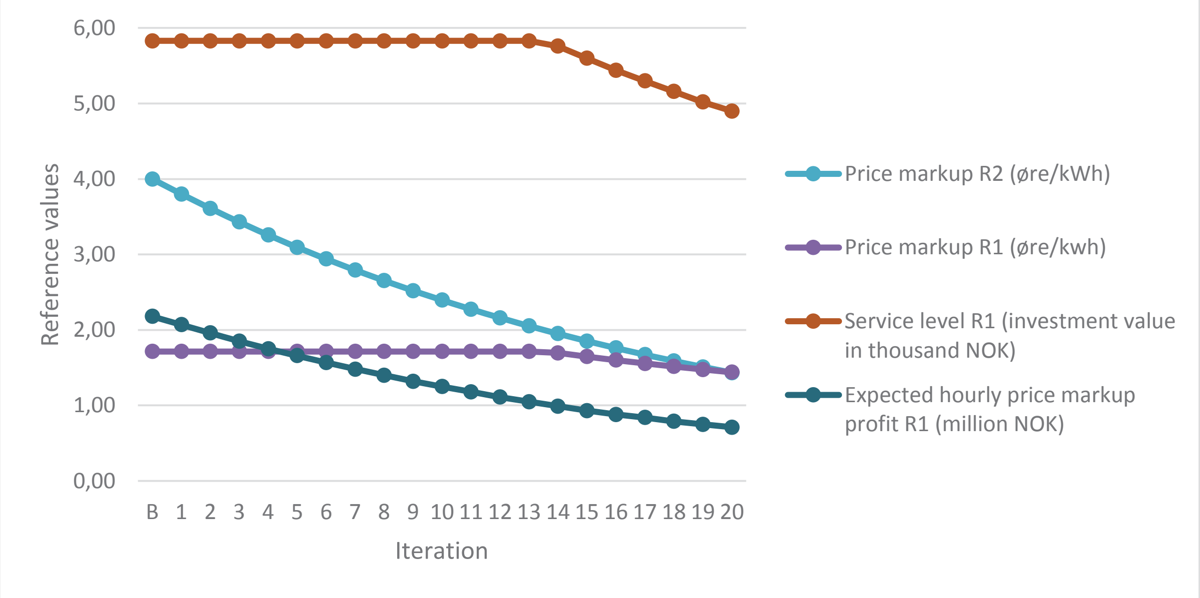

Figure 7 – Impact of decreasing the price markup for retailer 2 on retailer 1' price markup, service level and hourly profit

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.

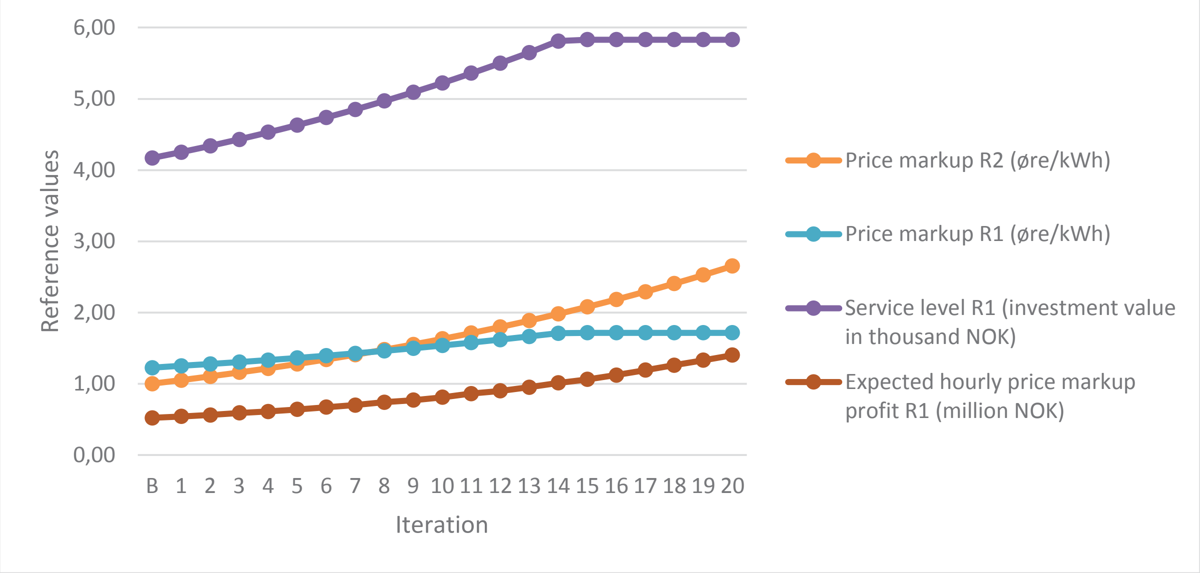

Figure 8 – Impact of increasing the price markup for retailer 2 on retailer 1’ price markup, service level and hourly profit

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.

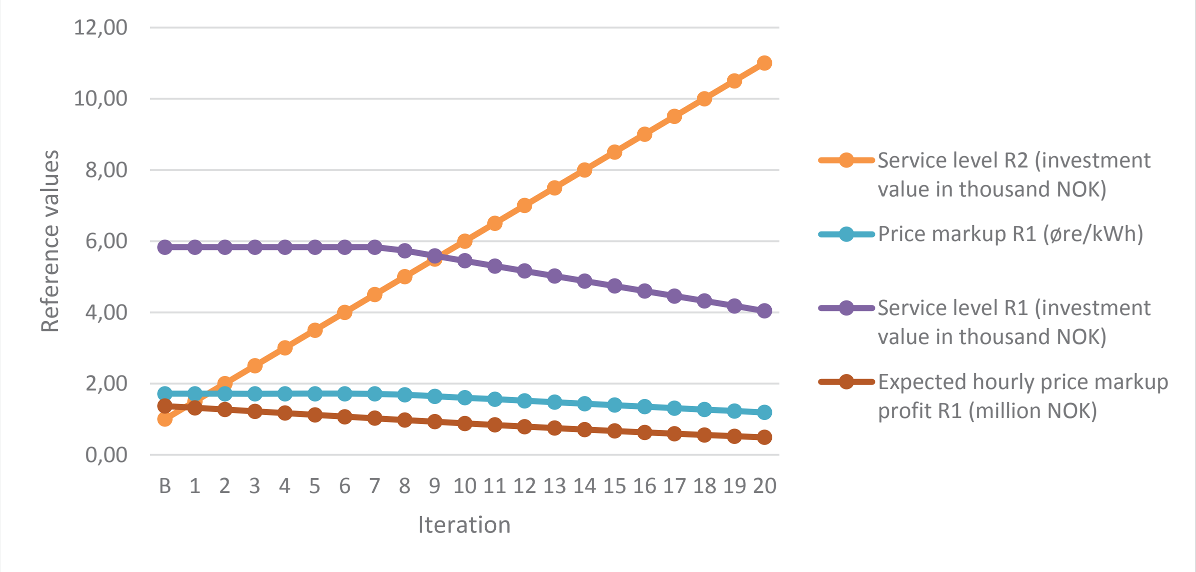

Figure 9 – Impact of increase in the service level for retailer 2 on retailer 1’ price markup, service level and hourly profit

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).

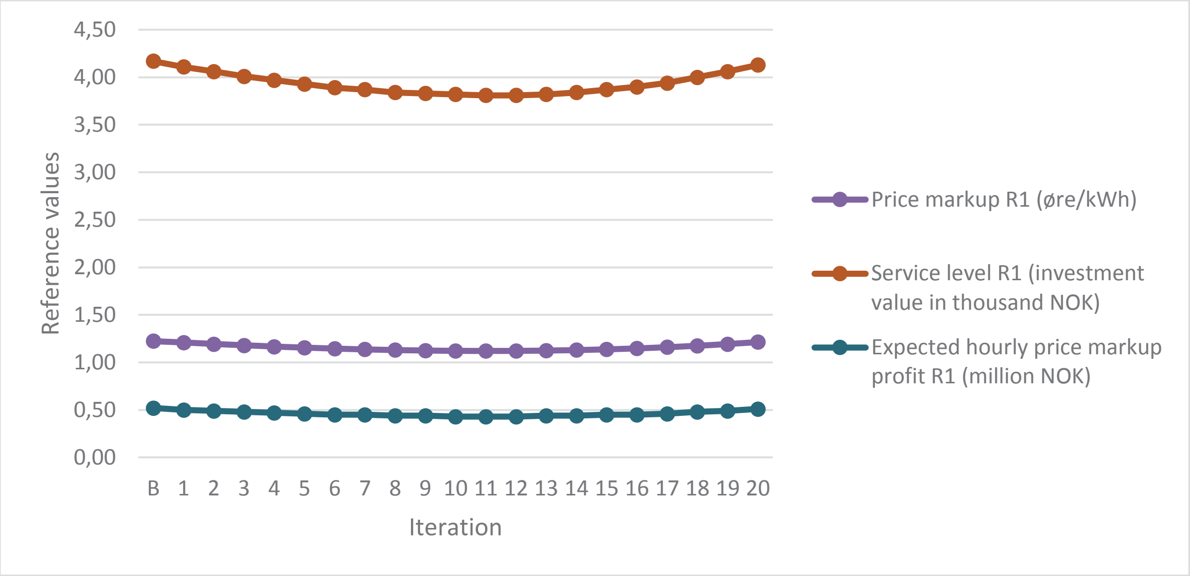

Figure 10 – Impact of increasing both the price markup and service level for retailer 2 on retailer 1's price markup, service level and hourly profit. Price markup and service level for retailer 2 are increasing as in simulations 2 and 3

Simulation 5: 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.

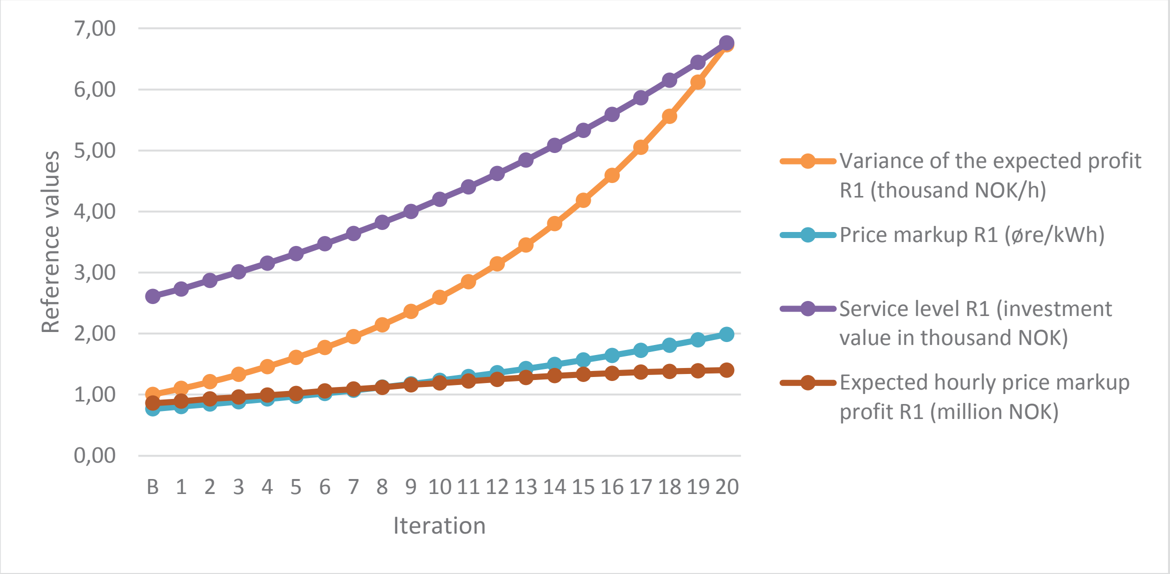

Figure 11 – Impact of increasing the variance of the expected profit for retailer 1 on retailer 1's price markup, service level and hourly profit.

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).

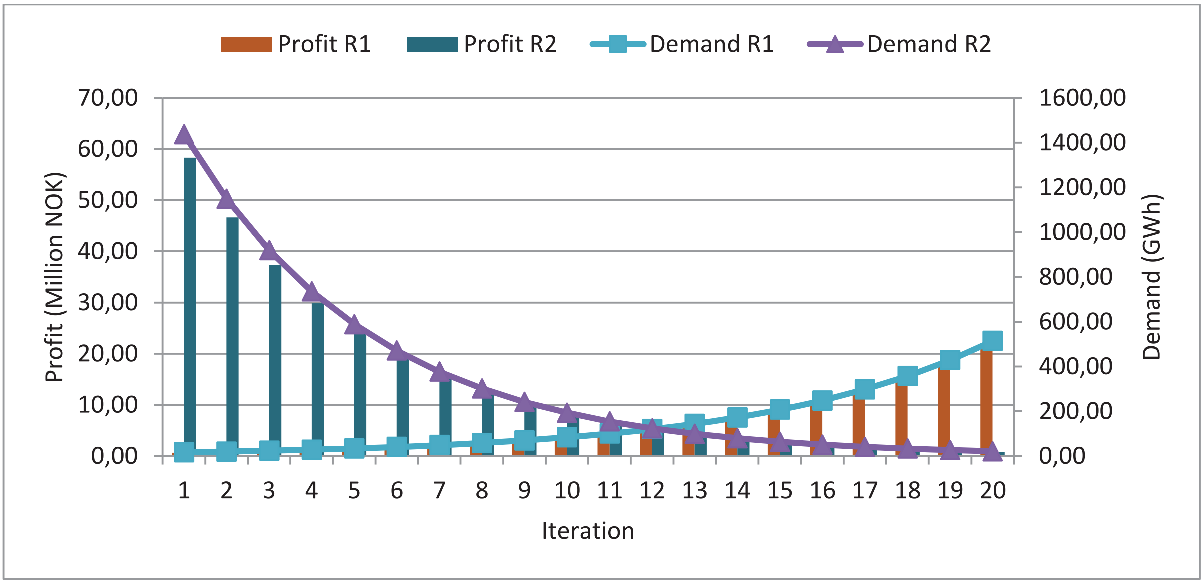

Figure 12 – Retailers’ yearly price markup profit when demand changes: small (R1) versus large (R2) company

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.

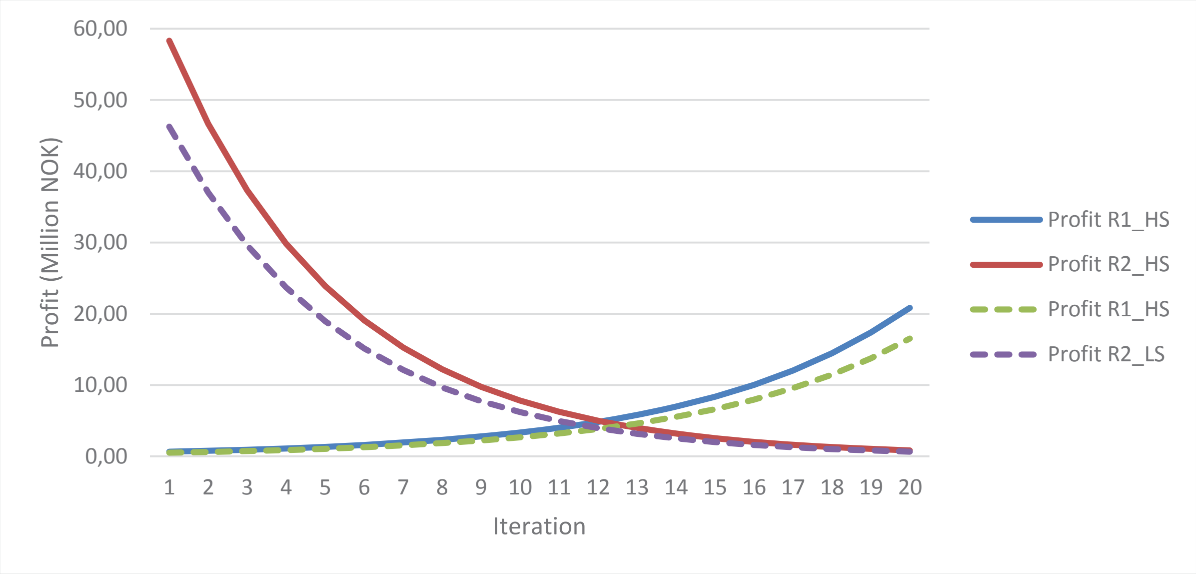

Figure 13 – Changes in the yearly profit for two retailers of different size when the ability of retailer 2 to innovate in service is decreased (from HS to LS). Dashed lines present the reduced profit.

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.

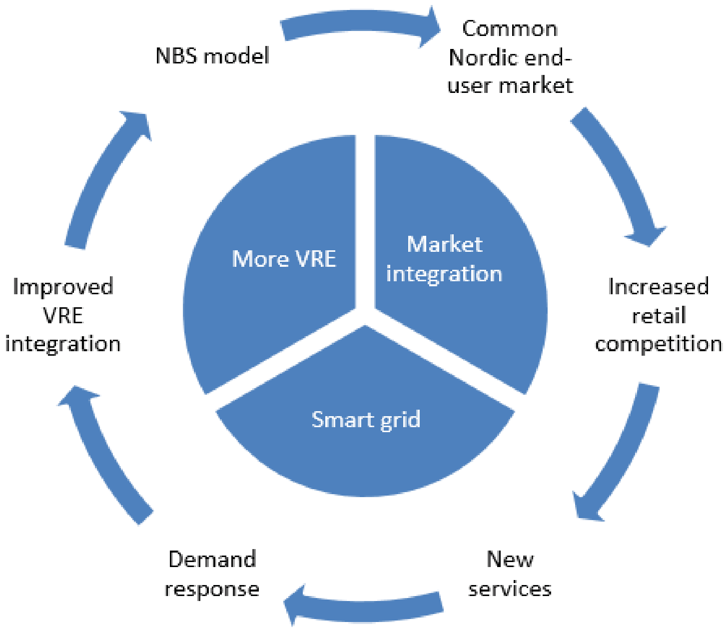

Figure 14 – Key issues discussed in Papers I-IV and their connection. The three major market changes lying in the core of the research articles are presented in the center.

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-

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[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
Ilieva, I. & Bolkesjø, T.F. 2014. An econometric analysis of the regulation power market at the Nordic power exchange. - Energy Procedia 58: 58–64.
DOI: 10.1016/j.egypro.2014.10.409

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

Paper IV
Tveten, Å.G., Ilieva, I. & Bolkesjø, T.F. Electricity market impacts of increased demand flexibility enabled by smart grid.
(Submitted)

ISBN: 978-82-575-1296-5
ISSN: 1894-6402

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