Norwegian University of Life Sciences
Faculty of Environmental Sciences and
Natural Resource Management

Philosophiae Doctor (PhD)
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Energy system flexibility for variable renewable energy integration in Northern Europe

Fleksibilitet i energisystemet for integrasjon av variabel fornybar energi i Nord-Europa

Jon Gustav Kirkerud

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SUMMARY

Variable renewable energy (VRE) is expected to grow considerably all over the world driven by ambitious targets for climate change mitigation. When VRE replaces dispatchable power plants, the flexibility of the power system is reduced. The Nordic energy system has opportunities to exploit large flexibility resources to a relatively low cost. Hydropower with reservoirs are well fitted to provide flexibility for VRE integration which is possible through better interconnection between regions with large amount of hydropower and neighboring regions where this flexibility is demanded. Another important option to increase flexibility is to create a stronger coupling between the power system and the large district heating sector in the region. This can be done through increased use of power-to-heat (P2H) applications such as electric boilers and heat pumps. This thesis identify and quantify the possible benefits of increased use of these flexibility options.

Analyses are carried out by applying the energy system model Balmorel, which is further developed to fit the aim of the study. Constraints to accommodate for linear models' lack of ability to represent thermal power plant cycling is added. A tool to create hourly profiles for heat consumption suitable for use in energy system model is created. Furthermore, to better analyze the operating conditions and the effect of grid tariffs in a district heating plant, a simulation tool is created.

The results show that the development of the heating market will be important when determining the future of the Nordic energy system. Converting old fossil fuel based boilers in Norway to stand alone electric heaters could cause near shortage situations and drive up prices significantly in years when the power surplus is low. A development emphasizing flexibility will give higher market values and competiveness for VRE.

Stronger integration between the hydropower dominated Nordic regions and neighboring thermal dominated regions result in increased market values of renewables. For wind producers the increase can be up to 6 % and a substantial increase in revenues for reservoir hydropower is also seen. Much of the value increase can be attributed to the system's ability to take better use of storage and differences in VRE generation patterns.

Furthermore, the structure of electricity grid tariffs has major impact on the profitability of P2H applications. Adaption of more novel tariff schemes increases the economic value of an electric boiler by 95 % to 174 % in the case study examined. This is in part because dynamic tariff designs gives an incentive for P2H to exploit periods with low power prices.

The potential for using the Nordic district heating system to ensure high competitiveness of VRE is found to be large. In a normal hydrological year and assuming high capacity in electric boilers, P2H may consume 11 TWh of electricity. In a year with wet hydrology, the consumption amounts to 19 TWh and will further increase if lower CO_2 prices are assumed. The effect on power prices is significant: a 5 % increase in a normal year and a 49 % increase in the wet year. Additionally, in areas with high VRE penetration, VRE generators see an even larger increase in revenues. It is shown that in addition to provide short-term flexibility, P2H can reduce the long-term price variations resulting from inter-annual weather differences and changes in fuel and emission prices.

List of papers

This thesis consists of the following papers

Paper I	Kirkerud, J. G., Trømborg, E., Bolkesjø, T. F. & Tveten, Å. G. (2014). Modeling the power market impacts of different scenarios for the long term development of the heat sector. *Energy Procedia*, 58: 145-151.
Paper II	Tveten, Å. G., Kirkerud, J. G. & Bolkesjø, T. F. (2016). Integrating variable renewables: the benefits of interconnecting thermal and hydropower regions. *International Journal of Energy Sector Management,* 10 (3): 474-506.
Paper III	Kirkerud, J. G., Trømborg, E. & Bolkesjø, T. F. (2016). Impacts of electricity grid tariffs on flexible use of electricity to heat generation. *Energy*, 115, Part 3: 1679-1687.
Paper IV	Kirkerud, J.G., Bolkesjø, T. F. & Trømborg, E. (2017). Power-to-heat as a flexibility measure for integration of renewable energy. *Energy* 128: 776-784.

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1 INTRODUCTION

1.1 The role of variable renewable energy in energy system decarbonization

“No challenge poses a greater threat to future generations than climate change”, said Barack Obama in the president’s state of the union address in 2015 to emphasize the need for greater action on reducing carbon emission. There is a scientific consensus that anthropogenic carbon emissions will cause, if we do not act fiercely, “rising oceans, longer, hotter heat waves, dangerous droughts and floods, and massive disruptions that can trigger greater migration and conflict and hunger around the globe”. Obama’s statements signify the importance of the climate change threat and the political will to act which culminated in the Paris agreement (UNFCCC 2015), negotiated in the 2015 United Nations Climate Change Conference in Paris. All the participant parties agreed to a goal of limiting global warming to well below 2 degrees Celsius compared to pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees. The agreement also states that zero net anthropogenic emissions must be reached within the second half of this century.

The most important cause for the rising emissions is the use of fossil fuels for energy purposes, mainly electricity, heating and cooling, and transport. Consequently, key strategies to fight climate change must include a radical transformation of the energy sector through energy efficiency, carbon capture and storage, and a shift to fossil free sources of energy. Among the fossil free energy sources, wind and solar photovoltaic (PV) shows especially large potential because deployment costs are declining and the resource availabilities are widespread and immense. The International Energy Agency’s (IEA) Energy technology perspectives (IEA 2016a) estimate a least cost pathway to limit energy sector emissions to a level that reaches the two-degree target with 50 % certainty. The report projects that wind and solar energy will provide 31 % of global electricity by 2050. Accordingly for Europe, the European commission predict a combined wind and solar share of 36 % by 2050 (EC 2016).

The Nordic energy system is characterized by already high shares of fossil free electricity generation from renewables and nuclear energy. In 2013, the carbon intensity in electricity generation was 59 g/kWh compared to a global average of a little more than 500 g/kWh (NETP). The region has abundant supply of hydropower resources in the north, large forests supplying biomass for energy and good wind resources in many parts. However, future growth in renewable electricity generation will largely come from wind power as most hydropower potential is already utilized and bioenergy may be used for other purposes where decarbonization is more costly, such as the building and transport sector. Through electrification, wind power can not only replace the remaining fossil based power generation in the Nordic countries, but also be used to decarbonize light duty transportation and heat generation by using heat pumps or electric boilers (IEA 2016b). In addition, by increasing electricity interconnection capacity to neighboring countries, Nordic renewable energy can be exported and substitute fossil fuel based electricity generation. Nordic energy technology perspectives (IEA 2016b) estimate that wind energy might account for 30 % of the produced Nordic electricity in a scenario where the Nordic countries are carbon neutral. With predictions that the future energy system will incorporate such high amounts of wind power, more thorough analyses of how to cope with such inflexible generation are called for.

1.2 Challenges of variable renewable power integration

Energy sources such as wind and solar power are labeled variable renewable energy (VRE) sources, pointing out their difficulty to match the also-varying electricity demand. With increasing shares of VRE, the risk of situations with over-supply of electricity will increase; meaning the value of the electricity generated is very low in some periods (Ueckerdt et al. 2015). On the other hand, other forms of generation must be kept in the system to cover peak-load because the capacity credit of VRE is often low (Holttinen et al. 2011). It may therefore be necessary to remunerate capacity costs in order to maintain desired generation adequacy. High shares of VRE may in addition increase cycling costs of thermal power plants, ancillary services costs, and imbalance costs due to forecasting errors (Hirth 2013).

These elements affect the economic value of the VRE source. For an overview, the marginal economic value of VRE can be decomposed into four components following electricity market structure and based on Mills and Wiser (2012):

i) *Market value*, or energy value, is the short-run revenue earned on an energy-only spot market. The market value reflects the contribution of a VRE source to reduce the energy system’s fuel, emission, and variable operating expenses. Cycling costs for thermal power plants are reflected in the market value if the market allows block bids. Frequent oversupply of VRE leads to very low VRE market values.

ii) *Capacity value* reflects the contribution of a VRE source to cover peak-load in the energy system. The capacity value is determined by the capacity credit of the VRE source and the costs associated with maintaining system generation adequacy.

iii) *Forecast error value* is the net benefit of deviating from the day-ahead generation schedule and is determined in the intraday and balancing markets. As forecasting errors for VRE are common, this component is usually negative.

iv) *Ancillary services value* is the net contribution of ancillary services provided by the VRE source. Ancillary services are managed by the transmission system operator (TSO) and usually means frequency control, reactive power and voltage control, and spinning reserves, which are typically provided by large power plants. This component is usually negative for VRE.

The most important components are market value and capacity value (Mills & Wiser 2012). Generally, with increasing shares the marginal economic value of a VRE source decrease (Hirth 2013; Mills & Wiser 2012). To counteract this deterioration it is beneficial to increase the power system flexibility (Lund et al. 2015; Mills & Wiser 2015). According to Müller (2014), measures to increase flexibility include: *i)* Demand side coupling to unleash the potential of flexible consumption, *ii)* install dispatchable generators with high production capacity and high ramping ability, *iii)* deploy energy storage that can move load from one period to another, and *iv)* integrate the system spatially by expanding grid infrastructure to connect to regions with more flexibility or VRE resources with other timing.

The Nordic region is rich in flexibility resources that can be utilized to a higher degree for VRE integration. The Nordic hydropower system can store water amounting to 120 TWh worth of electricity that can be used at short notice (Nordpool 2016). Through interconnections, this storage capacity provides flexibility for wind power in Denmark and nuclear power in Southern Sweden. At night time, or when wind power production is high, water is held back in the reservoirs as hydropower production is kept to a minimum. Conversely, hydropower is exported during daytime when the demand is high or when wind power production is low. This flexibility may also benefit neighboring thermal and wind power dominated regions such as Germany, Netherlands, and the United Kingdom if more interconnectors are built. These countries are expected to integrate high levels of VRE to replace fossil based dispatchable power plants, thus creating a need for more flexibility. According to Müller (2014), investments in interconnections have a favorable cost benefit ratio already today.

Another important flexibility resource in the Nordic energy system is the district heating system that can act as both a flexible electricity consumer and a flexible electricity producer.

Traditionally, combined heat and power (CHP) plants have provided a significant share in Nordic electricity production. Using power-to-heat (P2H) applications in district heating systems such as heat pumps and electric boilers is, however, an unexploited opportunity. Of the 110-135 TWh of annual district heat generated in the Nordics between 2008 and 2015 only 6 % comes from electricity on average (Energia 2013; Eurostat 2012). Increasing this share may be an efficient way to lower integration costs of VRE in the Nordic countries and surrounding areas while reducing emissions from district heating.

Although more flexibility will most likely be needed in the future because of higher VRE adaption, it is not obvious that flexibility measures should be incentivized through subsidies. This is because the market effects of integrating high shares of VRE give incentives for flexibility. For example, lower spot market prices due to high wind power production during a winter storm is a market opportunity for P2H as the district heating operator can reduce fuel expenses by switching to electricity in such events. However, policies and regulations may blur the incentives given by the market. End consumers often pay a fixed price for electricity rather than being exposed to price variations in the spot market. In addition, consumption of electricity is typically subject to various taxes and tariffs for transmission and distribution, which depending on the design can hamper demand side flexibility. Even in a situation with zero or negative spot prices during a winter storm where P2H is clearly economical in a system perspective, a high tax and grid tariff can result in continued use of other fuels such as natural gas for heating. Revising taxes and regulations is therefore regarded important when coupling the energy sectors with the aim to exploit inexpensive flexibility. The grid tariff is regarded particularly interesting as more flexibility can reduce peak-load and thus have the potential to delay or reduce costly grid expansions.

1.3 Goal and scope of the PhD project

In light of the challenges that arise from higher adaptation of VRE sources, it is important to gain insights in how flexibility options might help integrate more VRE. The goal of this thesis is therefore to analyze the benefit of two important flexibility options for the Nordic region in a market perspective. Firstly stronger market integration within the power sector through expansion of interconnectors between the Nordic region and its neighbors, and secondly the cross sectoral integration between the power and heat sector through P2H. How can the flexibility options increase power system flexibility and hence reduce VRE integration challenges in the Northern European energy system? The main objective is studied through the following sub objectives:

- Develop a Northern European energy system model that includes a detailed modelling of the power and DH sector and allows for realistic modelling of electricity trade between regions
- Identify the potential role and scale of the Norwegian heat market as a flexibility provider given two possible long-term strategic development paths
- Quantify role of Norwegian hydropower for integration of VRE in Northern Europe
- Analyze how grid tariff structures affect the flexibility provision from P2H in district heating
- Quantify the Nordic P2H potential and analyze the role in Northern European VRE integration

The research conducted for this thesis is presented in four research articles:

I) "Modeling the Power Market Impacts of Different Scenarios for the Long Term Development of the Heat Sector" published in Energy Procedia.

II) "Integrating variable renewables: the benefits of interconnecting thermal and hydropower regions" published in International Journal of Energy Sector Management.

III) "Energy system flexibility provided by the heating sector: Impacts of electricity grid tariff structures" published in Energy.

IV) "Power-to-heat as a flexibility measure for integration of renewable energy", published in Energy.

This synthesis report continues in chapter 2 with an analysis of the VRE and flexibility resources in the Nordic region based on existing literature. The objective is to give an overview of the basics of how the demand for flexibility is created and satisfied. Chapter 3 describes the methods used and explains the choice of models used to perform the analyses in this thesis. Strengths and weaknesses with the applied and alternative models are discussed. In chapter 4, the main findings in each research article is presented and discusses the implications of the findings, while chapter 5 concludes.

2 VARIABLE RENEWABLE ENERGY INTEGRATION IN THE NORTHERN EUROPEAN POWER MARKET

This chapter describes the characteristics of VRE in Northern Europe, discusses the market and system impacts, and describes the flexibility measures available.

2.1 VRE resources and characteristics in Northern Europe

Because wind and solar power are dependent on weather as the energy source, these VRE sources behave differently in the energy system compared to dispatchable power plants. Beside the benefit of generating electricity without fuel costs, VRE generation is characterized by being variable, uncertain, and often far from the electricity demand (Ueckerdt et al. 2015). A significant share of the integration cost can be credited to the fact that VRE supply is concentrated to relatively few hours of the year (Hirth 2013). Solar power is mainly concentrated to daytime hours in the summer when deployed in northern latitudes. In Germany in 2012, 50 % of annual solar power generation was concentrated to the 11 % sunniest hours (generation data from German TSOs (50hertz ; Amprion ; BW ; Tennet), own calculations). For wind power, 50 % of generation was concentrated to 21 % of the time. Measures to distribute generation from VRE to more hours will reduce the risk of overproduction and increase capacity credit. An example of such measures is low wind speed turbines who are designed to maximize performance at low and medium wind speeds. Similarly, solar panels can be angled slightly westwards or eastwards instead of straight south to maximize generation at medium high conditions. Such measures may increase the levelized cost of energy, but increased value of the energy may offset this cost.

Weather patterns for VRE production is random. Solar power generation largely follow the reliable diurnal and seasonal patterns caused by the earth’s orbit and rotation, but it is also subject to random patterns such as cloud cover (Mills 2010). Despite random patterns, solar power can on an aggregated level be counted on to contribute a fair amount of power on any given summer noon. Wind power cannot provide such certainty, although, clear diurnal and seasonal patterns in weather normals exist. In Northern Europe, wind power follows a weak diurnal pattern in the summer due to the sea breeze effect (Holttinen 2005; Mulder 2014), while there is a distinct seasonal pattern with more generation during the winter and autumn driven by the high cyclonic activity in the Northern Atlantic (Steiner et al. 2017) (figure 1).

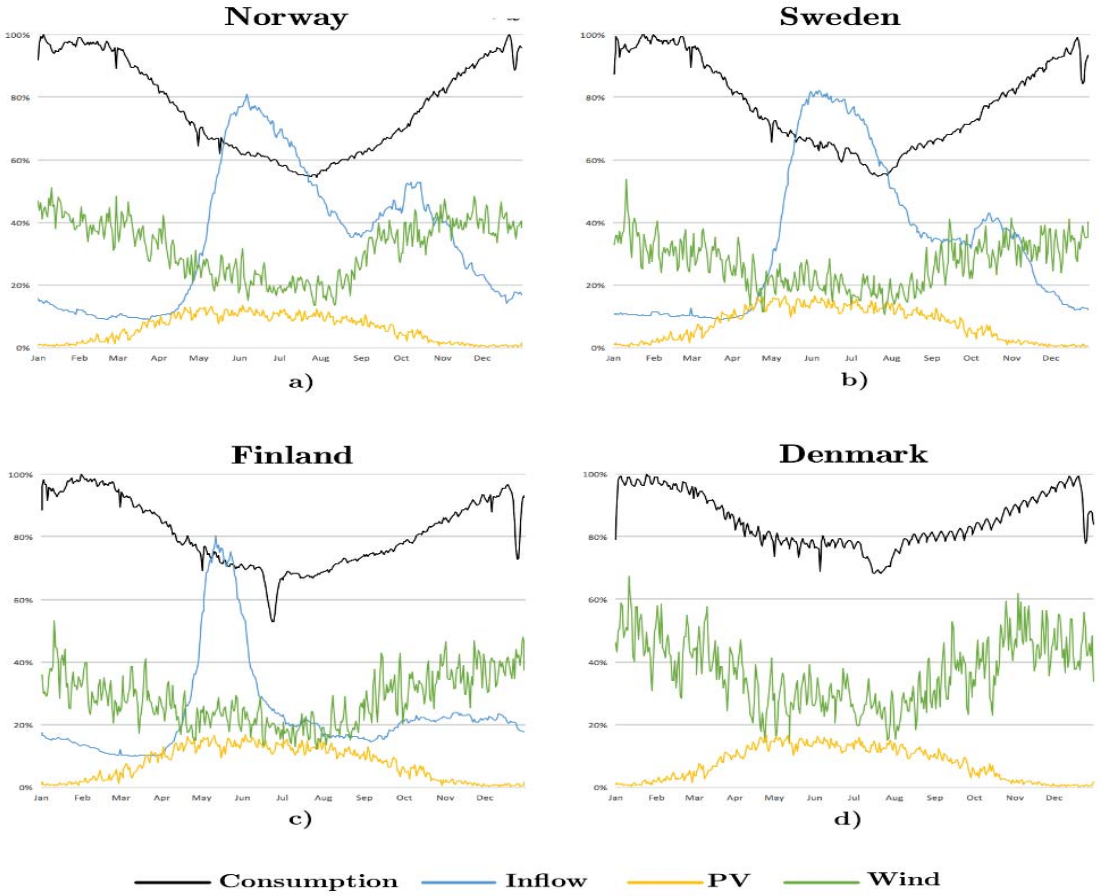

Figure 1: Seasonal variability in VRE resource supply and electricity consumption. Average hourly values for the years 2000 to 2012. Copied with permission from Grønborg (2016)

2.2 Market impacts and system challenges of integrating higher shares of variable renewable energy

In a day-ahead power market, such as the Nordic Nordpool spot, bids from the market players for each period are ranked into a merit order based on the bid price. Here, more VRE with no short-run marginal costs (SRMC) will outcompete generation that has higher SRMC in the bidding process. High VRE shares will in turn lead to lower market prices if enough high-SRMC generation is replaced, an effect labeled the merit order effect (Tveten et al. 2013). Consequently, all generators in operation in that period will earn less, while consumer's costs of electricity declines. Because VRE generation is often concentrated to relatively few hours of the year, the merit order effect may cause substantial reductions in the price received by VRE generators (market values) when the VRE shares increase. Low VRE market values can already be observed in the German market. In 2016, wind and solar had a market value of 25.0 and 26.8 €/MWh compared to an average spot price of 28.2 €/MWh (Burger 2016). This equates to a value of 86 % and 93 % relative to the average spot price for wind and solar respectively. While increased adaptation of VRE over time reduces installation costs due to scaling effects and learning rates, the economic value of VRE decreases as the penetration rates get higher (Hirth 2015). As long as the costs outweigh the benefits, subsidies are needed to enhance adaptation. With more flexibility in the energy system, higher market values for VRE can be sustained, thus reducing the need for subsidies to achieve a given target penetration of a renewable source.

VRE generation has a significant impact on generation patterns for other generators that must cover the gap between VRE generation and demand. VRE can cause more frequent and steeper ramps in net load, resulting in more part load operation and more start-ups and shutdowns, which are associated with considerable costs (Göransson et al. 2017; Kumar et al. 2012). High start-up costs can lead a power plant to bid negative prices for a few hours in order to avoid a short shutdown, as seen in Germany (Nicolosi 2012). Thermal power plants may convey ramping costs to the market through mechanisms such as block bids. These inflexibilities in thermal power plants increase fluctuations in the spot price caused by VRE.

Because VRE has the merit order advantage, most generators experience lower operation margins and operate at fewer hours of the year when more VRE is introduced. Dispatchable generation capacity may be reduced as a consequence. This reduces the flexibility needed to provide ancillary services, balancing, and peak-load generation capacity. Most VRE supply is random and full generation in peak-load situations cannot be guaranteed. The capacity credit, calculated as the reduction in net peak-load per installed capacity of VRE, measures the contribution of VRE sources to reduce system peak-load. Theoretically, a dispatchable power plant would have a capacity credit of 100 %, not accounting for outages. A meta-study (Holttinen et al. 2011) finds that the capacity credit for wind power varies between 5 % and 40 % depending on location and wind power penetration in the market. The capacity credit decreases with higher wind power penetration levels.

An increased share of VRE may cause impacts on resource adequacy in the inter-annual perspective. A common challenge in the Nordic power system is large yearly variations in hydropower inflow, which cause longer periods of low prices if the hydro balance is positive (wet) and periods of high prices if the hydro balance is negative (dry). Another factor adding to the imbalance is the outdoor temperature that determines the electricity demand for heating, which can be considerable in the Northern part of the Nordic countries. In Northern

Europe, correlation between high annual wind speeds, high hydropower inflow, and low outdoor temperatures cause large and prolonged imbalances in some years (Ely et al. 2013). If dispatchable capacity is replaced on behalf of VRE, the imbalances could increase while the flexible resources that can handle them decrease. Large price difference between some years could be the consequence.

2.3 The future development of the Nordic district heating sector

The Nordic energy system is characterized by well-developed district heating systems. As a comparison, the Nordic members of the EU (Denmark, Finland and Sweden) accounts for 29 % of all district heating demand for households and services in the EU (Eurostat 2012). The energy demand served by the Nordic district heating sector varies between 110-135 TWh depending on weather conditions (figure 2), amounting to approximately one third of the electricity market in the region. There is a slight increase in demand driven by Norway and Finland while further regional growth depends on several factors such as population growth, energy efficiency standards, and competitiveness of district heating compared to individual solutions. District heating is expected to stay competitive in areas with high heat demand density (Persson & Werner 2011), or places with access to low cost heat sources such as industrial waste heat and waste incineration plants (Connolly et al. 2014).

Annual heat generation from electric boilers or heat pumps amounts to 5-7 % of demand, indicating a significant potential for increased use of P2H. As seen in figure 3, Denmark and Finland have built the district heating systems around larger combined heat and power stations with a high share of fossil fuels and peat. The remaining share of fossil fuels, especially coal, is likely to be replaced in the coming decade according to action plans in relevant countries (IEA 2016b). In Sweden and Finland, a large share also comes from forest based biomass and byproducts from the forest industry. The future demand for forest based biomass as input in chemical industry and bio-fuel production is an uncertain factor having significant consequences for the future district heating system (Börjesson et al. 2017). While increased demand for these purposes will lead to higher biomass prices, waste heat from bio refineries might be used as input in district heating (Werner 2017). In Norway, the main share comes from waste incineration plants and more electricity is used in district heating.

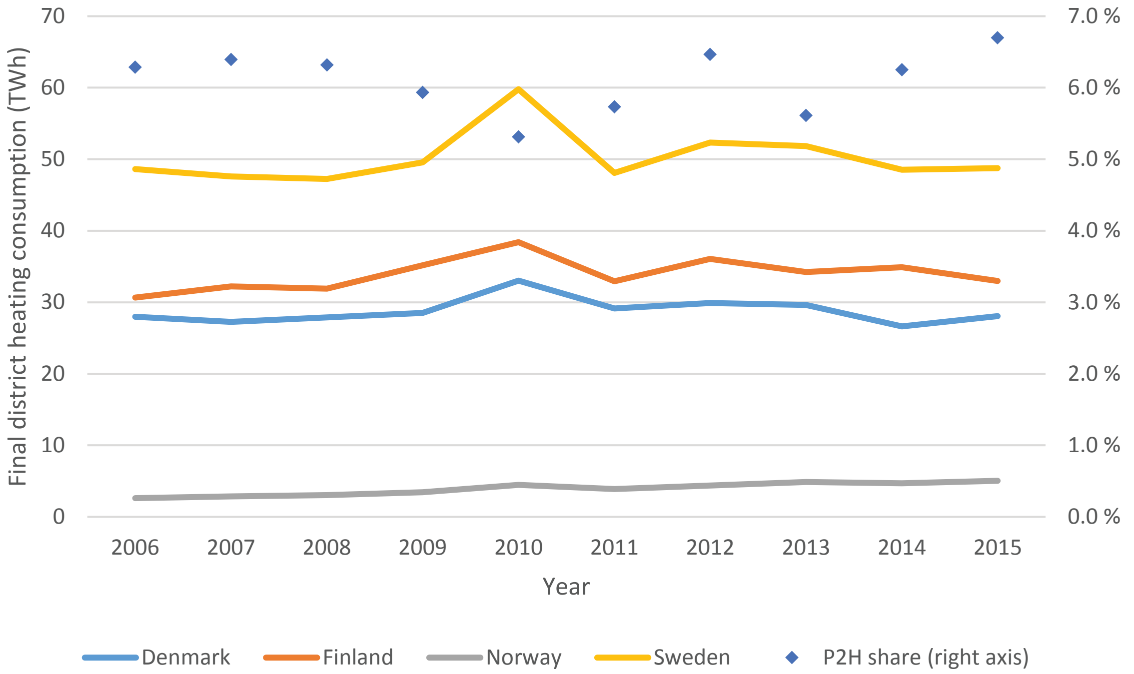

Figure 2: Development of delivered energy and share of electric boilers and heat pumps (P2H) of delivered energy in the Nordic district heating sector. Data from Eurostat (2012) and Stat.fi (2016)

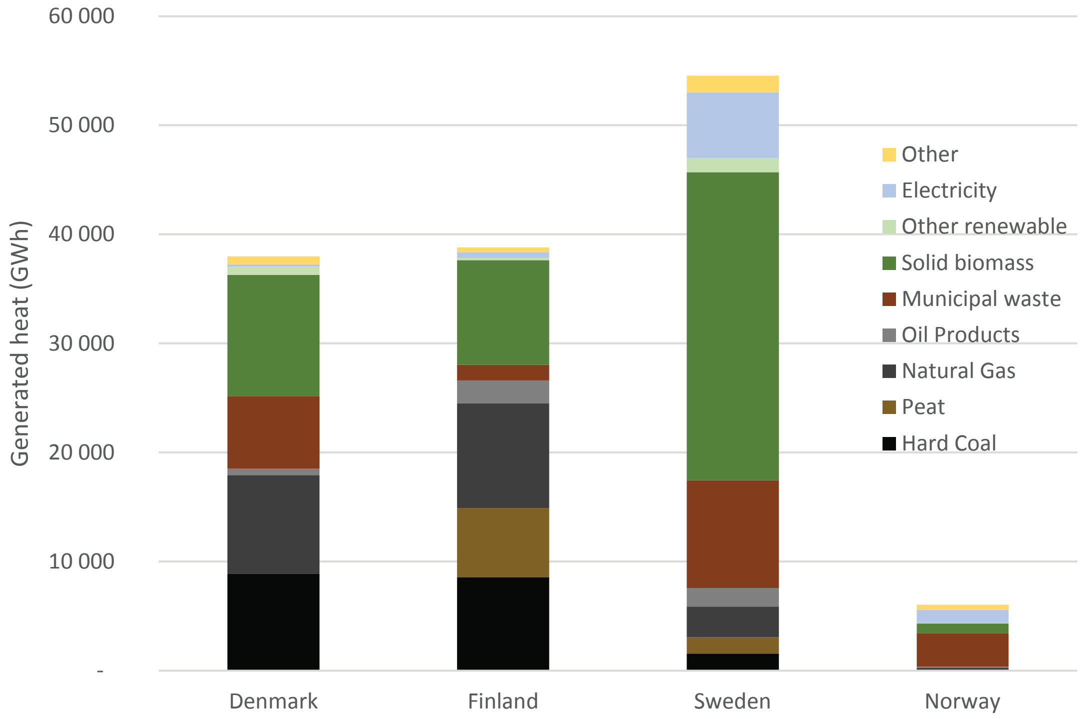

Figure 3: District heating generation in 2012 in the Nordic countries by fuel. Data from Eurostat (2012) and Stat.fi (2016).

2.3.1 Heat market flexibility

There are several sources of flexibility in a district heating system. The focus in this thesis is the flexibility accessible from switching between different heat producing boilers or technologies. Flexible electric boilers or heat pumps can be used to generate heat when electricity prices are low and other boilers or CHP when prices are high. Furthermore, flexibility in the heating system itself can be improved by installing heat storage, utilizing the flexibility in the district heating grid, or increasing end-user flexibility by taking advantage of the thermal energy storage in the building mass. Storing thermal energy is generally less expensive than storing electric energy (Lund et al. 2016).

The interaction of district heat markets and electricity market can be explained in detail using a merit order curve. Consider the example with a district heating system with four fuel-based boilers U_1 to U_4 and an electric boiler. The available supply by these boilers are ranked in figure 4 by short run marginal production costs P_H similar to a merit order curve typically seen for electricity markets. U_1 and U_2 represents typical baseload technologies, which in district heating systems could be municipal waste boilers or low grade bio fuels. U_3 and U_4 is mid-merit and peak-load technologies. In situation 1 we assume a high district heating demand, Q_H^1. If demand is to be met by the fuel-based boilers, even the expensive peak-load boiler U_4 must be used.

Depending on the electricity price, costs can be saved by replacing fuel-based heat generation with electric boiler generation. Figure 5 shows the bids from the electric boiler into the electricity market in situation 1 (el boiler bid curve 1). The price of the demand bids in the electricity markets corresponds to the marginal cost of the units in the merit order curve of the heating plant. For example, heat generation from municipal waste or waste heat from industry has near zero marginal cost U_1, hence the corresponding bid for the electric boiler to the spot market will be near zero or less ($B_{1.1}$). This way, district heating boilers can play the role as price setter in the electricity market. The difference between the price of U_1 and of $B_{1.1}$ is the efficiency of the electric boiler (η_{P2H}) and the tax and grid tariff cost ($T\&G$) from using the electric boiler (Eq.1). If wood pellet boilers were adapted in large scales together with electric boilers the impact could be significant as the demand bids would be in the typical range of electricity prices.

This also shows that DH systems heavily based on low cost sources such as heat from waste incineration have less potential to influence the power market because the demand bids will be very low. The dependency of heat demand is also clear; when heat demand is low, the overall demand bid from the electric boiler will be small in volume and only at low prices. This demonstrates how the composition of boilers in a heat only district heating plant affects the flexibility of P2H solutions. Combined heat and power complicates the picture as both operation of the CHP unit and the P2H unit is dependent on the power price and heat demand. Marginal heat production cost as a function of electricity prices is shown in figure 6.

$$B_{1.1} = U_1 \times \eta_{P2H} - T\&G \qquad \text{(Eq.1)}$$

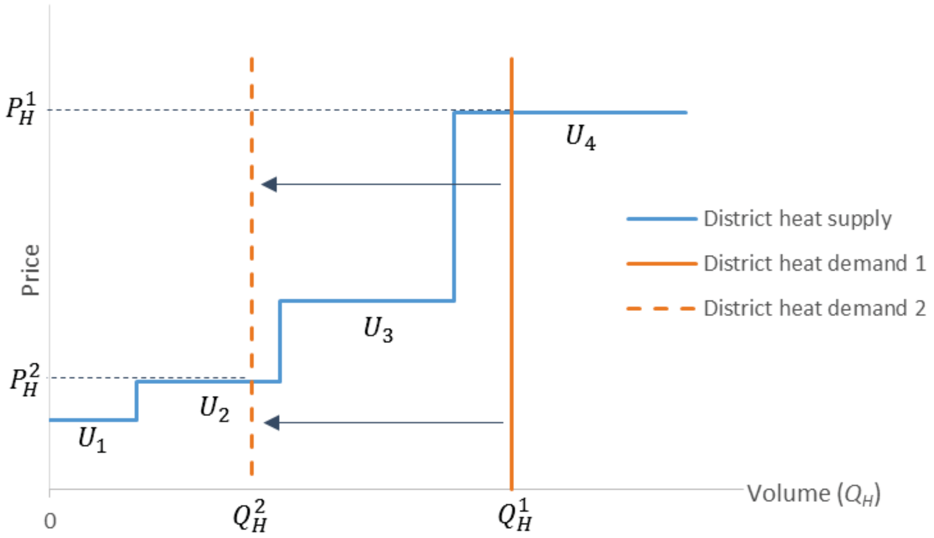

Figure 4: "Merit order curve" of heat generation for a district heating plant with four different heat only boilers (U_1 to U_4).

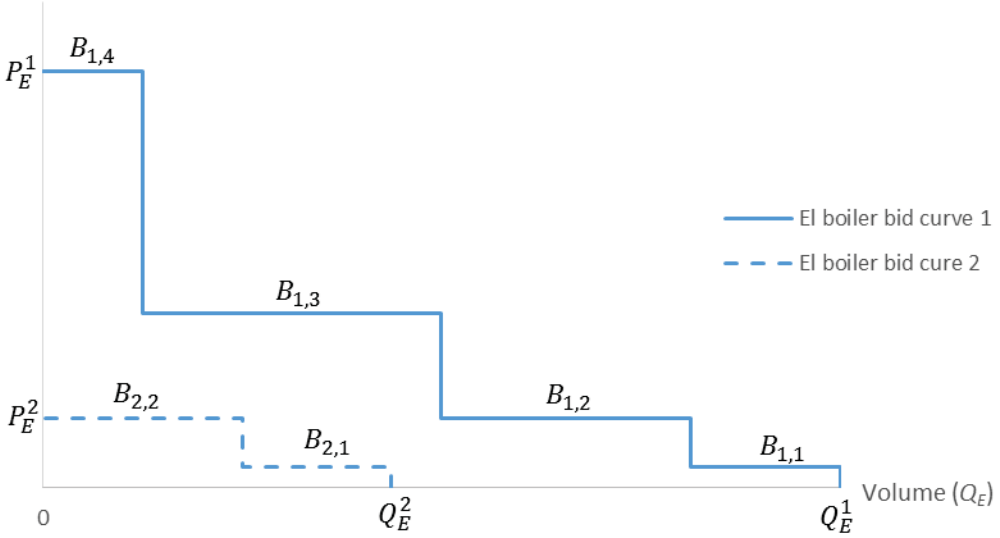

Figure 5: Resulting el-demand bids to the spot market to supply the electric boiler.

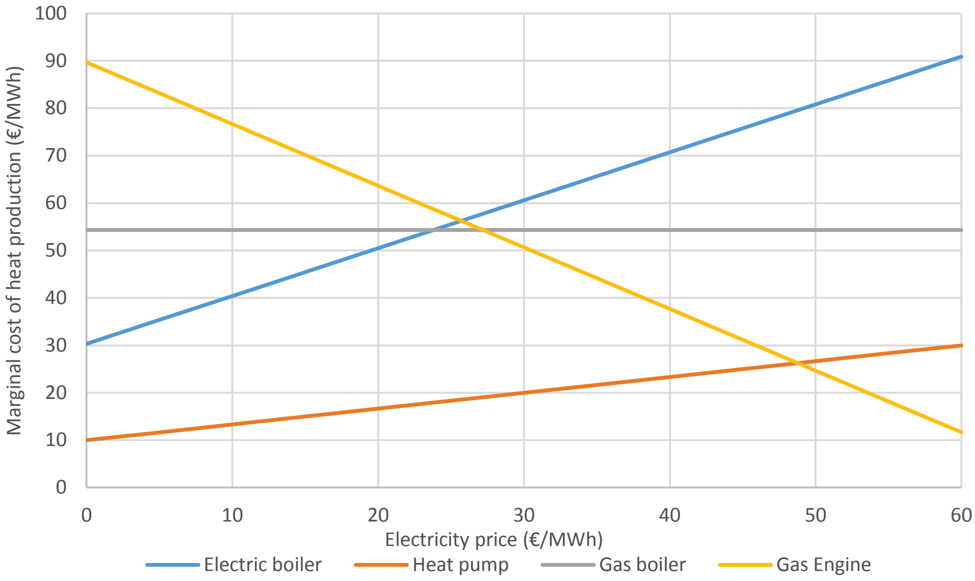

Figure 6: Marginal heat production costs as a function of electricity price for several typical district heating units. Assumed fuel cost and tax for natural gas is 50 €/MWh and assumed tax and grid rent for electricity is 30 €/MWh.

3 METHODS AND DATA

To analyze the identified problem, scenario analyses using energy system models were performed. The energy system model Balmorel was determined suitable for the analyses in paper I, II and IV. In paper III, a model with better representation of grid tariffs was chosen. This chapter contains a presentation of Balmorel and the reasoning behind the choice of this particular energy system model as well as a description of data used and model development for this thesis.

3.1 Criteria for choosing an energy system model

The energy system in focus for this thesis is the electricity market in Northern Europe and the interaction with the large district heating market in the Nordic region. Based on the characteristics of this particular energy system and the goal of the thesis, the following five criteria were considered important when choosing an energy system model and according characteristics of Balmorel:

i) *Hourly time resolution* is a natural choice as electricity markets such as Nordpool’s Elspot Day Ahead commonly use hourly contracts. Finer time resolution becomes more important with higher shares of VRE as fluctuations in generation are considerable even in short time spans. Hourly resolution captures much of the variation in VRE and the access data in this format is good. Both transmission system operators and Nordpool publish operational data with hourly resolution. However, this approach does not capture inter-hour aspects such as frequency control and effects of forecasting errors, which is important with very high rates of VRE. The Balmorel model can be adapted to hourly time resolution and is well suited to capture the dynamics in this time resolution.

ii) *A multi area model* capturing the flow of electricity between the model areas is necessary when modeling the Nordic electricity market and especially when investigating new transmission lines. In the Nordic market, some of the countries are divided into several bidding areas because of bottlenecks in the transmission grid. In Balmorel different geographical regions must balance supply and demand for electricity including trade. The flow of electricity is limited by transfer capacities.

iii) *Detailed modeling of district heating and the interaction with the power market*. Interaction between the electricity and district heating market is a central topic of this thesis and central in the Nordic energy market. In Balmorel, district heating can be generated by several technologies such as district heating boilers, waste heat, solar heat, heat storage, power-to-heat appliances, and combined heat and power.

iv) *Hydropower* is a key resource in the Nordic electricity market and needs particular attention in an energy system model. Balmorel distinguish between reservoir hydropower and run-of-river hydropower. Run-of-river hydropower act as other VRE resources, having an hourly availability profile and zero marginal cost. Reservoir hydropower can store inflow. To give a better representation of the water values for different reservoirs, Balmorel has the possibility to model as many reservoirs in each area as wanted. However, unlike stochastic models such as EMPS and SDDP (Hjelmeland et al. 2016; Warland et al. 2011), Balmorel uses a deterministic approach resulting in a too-perfect dispatch of water.

3.2 The Balmorel model

Balmorel is a detailed partial equilibrium model originally developed to model the Nordic and Baltic power and district heating sector (Münster et al. 2012; Ravn et al. 2001; Tveten 2015). The Balmorel model finds the least cost power and heat operation strategy in meeting the demand, given predefined power and heat generation capacities and transmission bottlenecks. The model solution provides market-clearing production, transmission levels and prices for each geographical unit and time step, under the assumption of competitive markets.

The current model version is updated with 2012 base year data (full model and data documentation are found in Tveten (2015)). The exogenous model parameters like demand, capacities of the different generation technologies, transmission capacity, and availability of variable renewable energy sources are specified individually for each power region and heat area. The model calculates the electricity and heat production per technology, time unit, and region, minimizing total system costs for a given electricity and heat demand. Market-clearing conditions in Balmorel are analyzed by applying two different modes of the model: i) a long-term (yearly) optimization horizon where the total reservoir hydropower generation is allocated on week level, and ii) a short-term (weekly) optimization horizon with an hourly time resolution where the weekly hydropower supply is allocated on an hourly basis.

The model version used for this study uses an exogenously decided generation capacity mix for a 2030 scenario. The production capacities are determined exogenously based on external sources such as the European commission roadmap to 2050 (Capros et al. 2014).

3.2.1 Model version and data sources

The power market module covers the Nordic countries, Germany, the Netherlands, and the UK (Tveten 2015). It has a detailed representation of the Nordic countries and especially the Norwegian and Swedish hydropower system, which may provide large amounts of flexibility. Other interconnected Northern European energy markets are handled as third countries with exogenously given power exchange. The main assumptions regarding installed capacities and consumption in the different modelled countries are reported in (Tveten 2015). For the electricity consumption, an observed hourly consumption profile of 2012 is applied to distribute the annual consumption over the modelled 8760 hours. The same year is applied as base year for hourly profile of wind and solar power. Fuel price assumptions are based on (EA-Analyse 2013; IEA 2014).

The district heating system is modeled in the Nordic countries with a finer spatial resolution: there are fourteen district heating areas in Norway, thirteen in Sweden, eight in Denmark, and seven in Finland. Assumptions regarding the installed DH boiler capacities in 2030 is based on (DEA 2013; Energia 2013; SSB 2013; Svensk_Fjärrvärme 2013).

3.3 Model development in this thesis

The present PhD work has contributed to further improvements of the Balmorel model in three main areas: (i) improved modeling of ramping of thermal power plants, (ii) district heating demand profiles based on outdoor temperature and consumer mix, and (iii) a side module that can compute the effects of grid tariffs on a detailed described district heating plant. These improvements are described in detail below.

3.3.1 Modeling costs of increased ramping in a partial equilibrium model

Unit commitment models are commonly used to represent thermal power plant cycling costs, i.e. power plant start-up, shutdown, or operating at sub-optimal levels. The challenge is that unit commitment models use integer variables, thus creating problems that are harder to solve. For this thesis, an approach using only linear formulations has been developed. With this add-on, “ramping costs” occurs when production output from a group of power plant changes from one hour to the next. While small ramps only induce a small cost per % change in output, large ramps are subject to high cost per % change in output due to a piecewise linear cost function. This is based on an assumption that the likelihood of a start-up, shutdown or part load operation increases with increasing power output changes from the power plant group.

To create the linear cost function each power plant group has three “ramping modes”. The first mode has no additional operational costs, but has a very small ability to ramp. The second mode has minor additional operational costs and slightly higher ramping abilities than mode one. The third mode have the highest additional operational costs and the highest ability to ramp. Ramping costs occur when the expensive mode replace a less expensive one due to increased ramping. Power output are constrained by the rated capacity of the power plant group both for the individual mode and for the sum of output from all three modes.

The ramping ability of mode three, i.e. maximum output change from one hour to the next for the group of power plants, are set according to observed operational data for the same plants. The ramping cost can be calculated as additional operational costs per MW of output change. The ramping costs of going from zero to full output using only mode three should not exceed observed start-up costs (Kumar et al. 2012). Apart from these anchors to empirical data, the parameters are given reasonable and conservative values determined through thorough model calibration for the base year 2012.

3.3.2 District heating consumption modeling

The hourly consumption profiles for electricity and heat are important input to Balmorel. While consumption profiles for electricity are easily obtained from Nordpool (2016) or ENTSO-E (2016), heat demand profiles are seldom publicly available. District heating consumption profiles varies from system to system because i) district grids are made up from different consumer groups and ii) outdoor temperatures are not perfectly correlated across the Nordic countries. Therefore, a model was made that generated consumption profiles based on a dataset for district heating consumers in Trondheim, Norway, temperature data across the Nordic countries, and information of consumer compositions in the different areas.

Statkraft Varme AS (Statkraft 2013) provided hourly data for year 2012 on DH consumption for 776 consumers in the Trondheim DH system in Norway. The data was indexed by consumer category and compared to the measured hourly outdoor temperature for Trondheim (eKlima 2013). To correct the load pattern for different temperature and consumer mix in the DH system, the relationships were found using linear regression models with auto regressive terms. A regression model (Eq.2) was created for each season of the year (s), consumer category (c), and hour of the day (h), assuming a linear relationship between outdoor temperatures (T_h) up to 17 degrees Celsius and consumption (C_h). The consumption in hour h is also dependent on the consumption in hour h-1 (C_{h-1}). The values for $\beta 1, \beta 2$ and $\beta 3$ was then connected to observed hourly outdoor temperatures (eKlima 2013; FMI 2015; SMHI 2015) and consumer mixes (Eurostat 2012) in key locations that represent the different heat areas in Balmorel.

$$C_{s,c,h} = \beta 1_{s,c,h} + \beta 2_{s,c,h} T_{s,c,h} + \beta 3_{s,c,h} C_{s,c,h-1} + \varepsilon_{s,c,h} \qquad \text{(Eq.2)}$$

The estimation model was validated against observed heat consumption in the Oslo DH system. The mean absolute error of the model is measured to 10.0 % compared to 21.1 % for uncorrected data.

3.3.3 MILP model for district heating plant operation with different grid tariff structures

A mixed integer linear program (MILP) for district heating plant operation with different grid tariff structures was built to analyze the operation of a single district heating plant. A detailed description and mathematical formulation is given in paper III.

4 MAIN RESULTS AND DISCUSSION

4.1 Market effects of the Norwegian heating sector

The power market effects of the Norwegian heating sector is addressed in Paper I where Balmorel is applied to analyze two scenarios. First, by removing the possibility to use electric boilers and, second, removing the stand alone oil-fired boilers in the central heating market and replace them with electric boilers and heat pumps.

The results show that the current flexibility in the heat sector reduces the strong price effect caused by inter-annual weather variations in the Nordic countries. In an energy surplus year with high levels of hydropower production and average power and heat consumption, the annual average market price in Norway decreases by 2.6 €/MWh from a level of 27 €/MWh if there is no possibility to use electric boilers. In a year with an energy deficit caused by low hydropower production and high demand of power and heat, the market price for electricity decreases by only 0.3 €/MWh from a level of 55.7 €/MWh. The opposite occurs when the oil-fired boilers are removed; in the surplus year, only a slight increase of 0.1 €/MWh, compared to an increase of 4.2 €/MWh in the year with energy deficit.

The impacts on VRE market actors are also clear; in the surplus energy year, market values for Nordic run-of-river hydropower and wind power experience a stronger decline than the average power price if electric boilers are excluded from the market. Norwegian run-of-river hydro experience the strongest effect with a decrease in market value of 11.4 % compared to the average price decrease of 9.7 %. On the other hand, if oil-boilers are replaced by electric boilers and a year with energy deficit occurs, market values of run-of-river hydropower will increase, but not as much as the average power price. This indicates a lower value factor for run-of-river power plants in both scenarios. Wind power in Norway and Sweden may conversely obtain a higher value factor in an energy deficit year where electric boilers replace oil-boilers. The market value increases slightly more than the average power price. This stems from the low wind power penetration level assumed in Norway and Sweden and the correlation of the seasonal profiles for both wind power and power consumption that are both higher in the winter.

4.2 Impacts of stronger transmission coupling between hydropower dominated Nordic countries and continental Europe

The benefits of stronger coupling between hydro and thermal regions are analyzed in Paper II. This scenario study analyze the short-term effects of changing the levels of transmission capacity between the hydropower-dominated Scandinavia and the thermal-dominated continental and British systems. The results show that in the year 2030, the power flow on the interconnectors will largely follow the VRE generation profiles flowing north towards the hydro reservoirs in high wind periods and south towards Germany in periods with low wind. Surprisingly, the planned interconnection expansions are found to increase average electricity prices in all regions except in the UK, because the number of hours where the electricity price is zero is reduced. However, further expansion of interconnectors does not have the same effect. Interconnection levels significantly reduce short-run power price variation in thermal countries and increase them slightly in Norway.

More interconnectors benefit VRE. The market value for wind power increase in all regions, and the value factor for wind increase in all regions except in Norway and Sweden where the value factor is relatively high. Across the modeled countries, wind generators experience a revenue increase of 2.9 % in the scenario where existing transmission plans are realized, and 5.1 % in the scenario where transmission plans are doubled. This is both because market value is increased and because curtailment is reduced. For run-of-river hydropower the revenue increases as much as of 6.1 % with the planned interconnections, but higher interconnection capacity does increase revenues further. The revenue increase for solar power is modest (0.9 %) because the market value is high even without the planned interconnection expansion. Natural gas and solids both receive lower market prices per unit with the planned interconnection expansions, but while natural gas generation decrease, the generation from solids increase. This leads to a strong decrease in revenue for natural gas of 11.8 % and a slight increase in revenue for solids of 0.8 %.

4.3 Importance of grid tariff design in modeling power-to-heat

The effect of grid tariffs on P2H operation in district heating is studied in Paper III using a mixed integer linear model simulating unit commitment and operation in a district heating plant with multiple fuel options including electricity. Two standard tariff structures, a flat rate design and a demand charge based design, and two kinds of dynamic tariffs, a critical peak price based design and a real time pricing scheme that follows electricity grid tariffs, are compared. The grid tariff structure are found to have significant impact on how district heating plant can contribute to short term flexibility by increasing power consumption in surplus periods while using fuel based boilers in peak periods. Dynamic tariff designs, which can vary on an hourly time scale, will imply low total cost of electricity in periods with both surplus electricity production and significant spare capacity in the electricity grid. Hence, electricity use is increased in these hours. The assumed demand charge, which mainly charge based on the consumer's peak consumption during a month, is found to eliminate electricity use in the winter. The other designs allows the district heating plant to exploit periods of low power prices in the winter. Most electricity use is observed when assuming a critical peak price based design that put a high charge on the 5 % hours with highest load, while the charge is small for the rest of the year.

The grid tariff designs do not only determine how much flexibility that can be provided by P2H in a short-term perspective, they also determine the economic attractiveness of P2H solutions and district heating plants in the longer term. Changes in tariff designs lead to changes in the plants total operating costs. The results show that a critical peak price design leads to the highest cost reductions for the DHP and is thus the most attractive design from a DHP perspective. The economic benefit of the P2H application, in terms of its ability to reduce variable operating costs for the district heating plant, is increased by 95 % to 174 % when changing from the most attractive standard tariff design to the critical peak price design. Moreover, the income to the grid operator through grid tariffs from the P2H use is also influenced and is largest with the flat rate tariff structure. However, going from flat rate tariffs to critical peak tariffs leads to larger reductions in DHP operating costs than reductions in DSO income, thus indicating an efficiency gain. To further evaluate these effects, more sensitivity studies on e.g. energy and fuel taxes are recommended.

4.4 The Nordic district heating market as a flexibility provider

The role of P2H as a flexibility provider for the Nordic district heating market is studied in Paper IV by including the Nordic district heating sector in Balmorel. Analysis of the market conditions in a 2030 scenario is carried out with different pre-defined levels of electric boiler capacities in the district heating sector; 0, 10, 20 and 50 % of peak heat load in every district heating grid. Results show that electricity use in district heating is up to 11 TWh in a year with normal hydropower inflow and up to 19 TWh in a year with high hydropower inflow.

In a future Nordic electricity market that relies to greater extent on wind power and has stronger interconnection with neighboring thermal and wind power based electricity markets, P2H in district heating contributes to stabilization of the power markets. Even with moderate installed capacities in electric boilers, P2H significantly drive electricity prices upwards. The effect stands out when assuming a year with high hydropower inflow. Here, a change in electric boiler capacity level from 0 % to 20 % induce the power price to increase 49 % from the low price level seen in the wet year. Assuming normal inflow conditions, the price increase is 5 %. The market value for VRE change accordingly with a particularly high increase during the wet year for run-of-river hydropower that experience an increase of more than 70 % in the 20 % scenario. Furthermore, an analysis of the value factors show increased competitiveness of wind power in most regions. The hydropower dominated regions in Norway and Sweden experience only minor changes in the value factor for wind power while the change is particularly large in East Denmark. The difference is most significant in years with normal hydrological conditions. This result suggests that P2H as a measure to provide short-term flexibility is greatest in thermal dominated regions with little influence of reservoir hydropower.

The use of P2H is sensitive for the CO_2 prices as fossil fuels still play a significant role in the assumed Northern European power system in 2030. Changing the CO_2 price from 5 €/ton to 50 €/ton lead to a decrease in P2H use by15 TWh in the normal year and 19 TWh in the wet year. This means that P2H could play a role in hedging against uncertain fuel and emission prices.

4.5 Discussion and further work

This thesis contributes with valuable insights to the debates of how to handle the large shares of new variable renewables that is necessary to achieve ambitious targets to limit climate change. The focus has not been on innovative flexibility technologies that need more research and deployment in order to be economically attractive, but rather on exploiting the potential for flexibility embedded in the characteristic Nordic energy system. Although investment costs are not included in this study, a strategy aiming to facilitate the suggested flexibility measures is considered to be cost efficient. A new interconnection may be fully financed by bottleneck income (Müller 2014) and P2H in district heat may replace investment and fuel costs for alternative boilers.

This study gives insights in how possible pathways for the Norwegian heating market influence the power system, quantify benefits of better interconnection between the hydropower dominated Nordic regions and surrounding thermal dominated regions and finally contributes to the discussion of how grid tariffs should be regulated in a future with more VRE. The improved energy system model now covering both the Nordic power market and the district heating sector, is well suited to capture the price effects of introducing various forms of flexibility resources.

The results showing the market value effects of increased flexibility in the system is in line with other studies such as Mills and Wiser (2015). More flexibility in the system most often benefits VRE. The exceptions are when VRE initially has a high value factor as for example with Norwegian wind power, which benefit from short-term flexibility from hydropower and seasonal correlation with electricity and heat demand. This suggest that the benefit of the flexibility will be higher in scenarios with higher shares of VRE. Increased market values for VRE as a result of increased flexibility imply that less subsidies are needed to reach a given share of VRE, given that the VRE revenues are dependent on market prices. Subsidies are often associated with cost inefficiencies (Kalkuhl et al. 2013).

In addition to be an option to increase flexibility in the power market, P2H may be a cost efficient way to replace heat generation based on fossil fuels. This is particularly interesting if the fossil fuel based generation replaced is not included in the EU’s emission trading scheme. In such case, P2H will give guaranteed reduction of CO_2 emissions. Compared to today’s share in the Nordic district heating mix of around 6 %, results show that with electric boilers alone the share can easily reach more than 10 % in wet years. However, uncertainty regarding what role biomass will play in a future energy system, as the feedstock can be used for multiple purposes such as biofuels for the transport sector, leads to uncertainty in the potential of P2H. A higher biomass price will probably lead to a greater potential of P2H.

The study has identified important benefits for VRE of introducing greater amounts of flexibility resources into the system. Energy markets are dynamic, especially in a long-term planning perspective where investment in new equipment and foreclosures of old is taken into account. Therefore, applying a short-run perspective as in this thesis will cause overestimation of some price effects. For example, the increased market value for VRE as a result of more flexibility will in principle lead to more VRE investments in a long-run perspective. A consequence of high shares of VRE pushing electricity prices down is that many generators struggle to keep profitable. For the security of supply it is crucial that the markets are able to generate enough investments to satisfy peak demand of the system. In future research, this question could be better addressed if a long-term approach was applied.

In this thesis two different measures to increase flexibility in the power system were investigated, namely sector integration between the power and heating market and interconnection between power regions. However, other options to increase power market flexibility are available and expected to be important in the future. The interaction and competition between flexibility options will therefore be relevant, but comparing them is a complex task as some technologies are actors in several markets, e.g. balancing markets, and some are also dependent on revenues from other sectors, such as hydrogen. Generally, if there were a level playing field, cheap sources of flexibility should outcompete the more expensive ones. A priority for future research should be to apply a more holistic method in this matter.

5 CONCLUSIONS

The goal of this thesis was to analyze how VRE sources in Northern Europe could be better integrated by using the Nordic flexibility resources in hydropower and the district heating system. On the Balmorel framework, an energy system model for Northern Europe with emphasis on the Nordic market was developed. It is considered well suited for analyzing benefits of stronger sector coupling between the power and the district heating and better interconnection between the power regions.

The results show that the development of the heating market will be important when determining the future of the Nordic energy system. Converting old fossil fuel based boilers in Norway to stand alone electric heaters could cause near shortage situations and drive up prices significantly in years when the power surplus is low. A development emphasizing flexibility will give higher market values and competiveness for VRE.

Stronger integration between the hydropower dominated Nordic regions and neighboring thermal dominated regions result in increased market values of renewables. For wind producers the increase can be up to 6 % and a substantial increase in revenues for reservoir hydropower are also seen. Much of the value increase can be attributed to the system’s ability to take better use of storage and differences in VRE generation patterns.

Furthermore, the structure of electricity grid tariffs has major impact on the profitability of P2H applications. Adaption of more novel tariff schemes increases the economic value of an electric boiler by 95 % to 174 % in the case study examined. This is in part because dynamic tariff designs gives an incentive for P2H to exploit periods with low power prices.

The potential for using the Nordic district heating system to ensure high competitiveness of VRE is found to be large. In a normal hydrological year and assuming high capacity in electric boilers, P2H may consume 11 TWh of electricity. In a year with wet hydrology, the consumption amounts to 19 TWh and will further increase if lower CO_2 prices are assumed. The effect on power prices is significant: a 5 % increase in a normal year and a 49 % increase in the wet year. Additionally, in areas with high VRE penetration, VRE generators see an even larger increase in revenues. It is shown that in addition to provide short-term flexibility, P2H can reduce the long-term price variations resulting from inter-annual weather differences and changes in fuel and emission prices.

Future studies addressing flexibility options for the energy system should take into account the long-term perspective to address the ability to cover peak-load in the system. Furthermore, competition between flexibility options should be better analyzed to give a better of what technologies that will be most valuable in the future.

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