Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management
Research Group of Renewable Energy

Philosophiae Doctor (PhD)
Thesis 2022:25

Emerging challenges in the energy transition in Northern Europe: potentials and impacts

Nye utfordringer i energiomstillingen i Nord-Europa: potensialer og virkninger

Yi-kuang Chen

Emerging challenges in the energy transition in Northern Europe: potentials and impacts

Nye utfordringer i energiomstillingen i Nord-Europa: potensialer og virkninger

Philosophiae Doctor (PhD) Thesis

Yi-kuang Chen

Norwegian University of Life Sciences
Faculty of Environmental Sciences and Natural Resource Management
Research Group of Renewable Energy

Ås (2022)

Thesis number 2022:25
ISSN 1894-6402
ISBN 978-82-575-1899-8

Supervisors

Professor Torjus Folsland Bolkesjø
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences

Dr Jon Gustav Kirkerud
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences

Evaluation committee

Professor Magnus Korpås
Department of Electric Power Engineering
Faculty of Information Technology and Electrical Engineering
Norwegian University of Science and Technology (NTNU)

Associate Professor Frauke Wiese
Department of Energy and Environmental Management
Europa-Universität Flensburg (EUF)

Professor Muyiwa Samuel Adaramola
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences

Table of Contents

Acknowledgements

I would like to thank Torjus Bolkesjø for being the best main supervisor one could ask for. It has been the right balance of guidance and trust for my independent work. I have appreciated our discussions and your advice, which have been essential to my research. I also want to thank you for your openness and encouragement and for making my PhD journey as smooth as it could possibly be.

I would like to thank my co-supervisor, Jon Gustav Kirkerud, for the insightful discussions and for building the foundation of my Balmorel skills. You have been the go-to person whenever I encounter difficulties in modelling or analysis tasks. I also would like to thank Hans, Marie, Ida and Hardi for sharing their knowledge in energy system modelling.

Thank you, Niels, for being a great colleague, officemate, neighbour and friend. I have enjoyed our work- and non-work-related discussions, constant snacking, lifts and trips. You are a big contributor to my social life in Ås and thank you for initiating many of my friendships with awesome people.

I also would like to thank Eirik, Anne and the colleagues in the renewable energy group for our lunch conversations and for creating an inclusive work environment. Thanks to all the helpful MINA people.

Many thanks to the research projects Flex4RES and NorENS for financing my PhD, and the project partners for providing useful comments and fruitful meetings.

My thank you list is still too long. I am grateful for all of you that played a role in my achievement and in my life in the past years. Most importantly, I would like to thank my family back in Taiwan, for being supportive as always and for trusting me.

Yi-kuang Chen (陳怡光）

Ås, November 2021

List of papers

Paper I	Chen, Y.-k., Hexeberg, A., Rosendahl, K. E. & Bolkesjø, T. F. (2021). **Long-term trends of Nordic power market: A review.** *WIREs Energy and Environment*, 10 (6): e413. DOI: 10.1002/wene.413 (Dataset DOI:10.18710/9EJYHX)
Paper II	Chen, Y.-k., Jensen, I. G., Kirkerud, J. G. & Bolkesjø, T. F. (2021). **Impact of fossil-free decentralized heating on Northern European renewable energy deployment and the power system.** *Energy*, 219: 119576. DOI: 10.1016/j.energy.2020.119576 (Dataset DOI: 10.18710/06HSDA.)
Paper III	Chen, Y.-k., Kirkerud, J. G. & Bolkesjø, T. F. (2021). **Balancing GHG mitigation and land conflicts: Alternative Northern European energy system scenarios.** Submitted to *Applied Energy* and under review.
Paper IV	Chen, Y.-k., Koduvere, H., Gunkel, P. A., Kirkerud, J. G., Skytte, K., Ravn, H. & Bolkesjø, T. F. (2020). **The role of cross-border power transmission in a renewable-rich power system – A model analysis for Northwestern Europe.** *Journal of Environmental Management*, 261: 110194. DOI: 10.1016/j.jenvman.2020.110194
Other papers	Bolwig, S., Bolkesjø, T. F., Klitkou, A., Lund, P. D., Bergaentzlé, C., Borch, K., Olsen, O. J., Kirkerud, J. G., Chen, Y.-k., Gunkel, P. A., et al. (2020). Climate-friendly but socially rejected energy-transition pathways: The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. *Energy Research & Social Science*, 67: 101559. DOI: 10.1016/j.erss.2020.101559. Gea-Bermúdez, J., Jensen, I. G., Münster, M., Koivisto, M., Kirkerud, J. G., Chen, Y.-k. & Ravn, H. (2021). The role of sector coupling in the green transition: a least-cost energy system development in Northern-central Europe towards 2050. *Applied Energy,* 289: 116685. DOI: 10.1016/j.apenergy.2021.116685.

Summary

The European energy transition has passed the initial stage, and both the speed and scope of decarbonisation are growing rapidly. Decarbonisation progress has been observed in the power sector, but stronger efforts are called for in the non-power sectors. The electricity generated from renewables can potentially supply other energy needs, such as heating and transport, as a clean fuel. Future electricity demand will grow, and more renewable deployment will be required. The growing carbon prices and the declining costs of wind and solar technologies contribute to the economic competitiveness of renewables against fossil-fuel based generation. Nevertheless, the increasing renewable deployment results in new challenges that are beyond the techno-economic aspects. This thesis presents a review of Nordic power market outlooks, followed by three model analyses to investigate how the new challenges might affect future energy systems.

The power market outlook review (Paper I) builds the foundation to narrow down the focus angles for the other model analyses in this thesis. The outlooks often use energy system models, which consist of three key components: demand, supply and interconnection, with techno-economic perspectives. These models perform techno-economic optimisations by system cost minimisation or total social welfare maximisation. The review shows that less attention is put on the demand side compared to the thorough analysis on the supply side, and the focus on end-use sectors is limited. On the supply side, more variable renewable energy is needed, but the onshore wind development might be restricted in the recent outlooks despite its cost competitiveness and the high power price outlooks. One potential barrier is the lack of social acceptance due to concerns over land requirements. All the review outlooks regard cross-border interconnection as a key piece of the energy transition, but some appear less positive than others as a result of welfare redistribution. Based on the review, the three remaining studies of the thesis focus on (i) decarbonisation for heating and impacts to electricity demand, (ii) renewable supply and land use conflicts, and (iii) economic impacts and dilemmas in cross-border electricity trade.

Papers II-IV apply and further develop the energy system model Balmoral. The standard Balmorel framework models the power and district heat sectors in Northern Europe. A new module of the decentralised heating sector is developed in Paper II to show its impact on the power and district heating sectors. The estimation shows that over 80% of the space heating and hot water demand in Northern and Western Europe is supplied by decentralised heating systems, which are yet to be decarbonised despite the already existing mature solutions. The modelling results show that electrification through heat pumps and hybrid systems are the most cost-effective solutions in reaching full decarbonisation. Assuming future heat demand similar as today, heating decarbonisation will need 700 TWh extra fossil free electricity, which consequently quintuples the installed wind capacity and increases winter load significantly. Paper II demonstrates the importance of coupling the power and non-power sectors in making the analyses for decarbonisation.

The other two papers (Papers III and IV) incorporate the non-techno-economic perspectives in the Balmorel model to assess their influences on the energy transition. A disadvantage of renewables is their large land requirement, which is often not explicitly addressed in techno-economic optimisation models like Balmorel. Paper III applies the modelling to generation alternatives concept to Balmorel to search for near-optimal future energy systems that cause the least land conflicts. The results show that the least cost system will require four times today's land use level for energy production. Increases in system costs can reduce land use by shifting the systems with more offshore wind and nuclear power, but the implied annual costs for saving land, €200 k/km^2 to €700 k/km^2, appear substantially high compared to the market prices of non-building land.

Paper IV applies a scenario analysis to quantify the economic potentials of cross-border interconnection. We compared one scenario with the modelled optimal transmission capacity reaching the least system cost to another scenario with given transmission capacity and with no expansion beyond 2030. The results suggest that an addition of 76 GW cross-border transmission capacity can lower system costs by 5% and CO_2 emissions by 40% between 2030 and 2050. Wind and hydro power producers in the Nordics gain the most from increased cross-border power transmission. Based on the model assumptions in this study, their revenues increase by 67%, while the Nordic consumer costs of electricity also increase by 21%. Increased consumer costs in export regions could contribute to significant resistance to increased cross-border electricity trade.

In line with other literature, the results in this thesis show that the energy transition will require a significant amount of electricity and renewable energy deployment. In addition, the thesis demonstrates the need for expanding the scope of energy system analyses, and it illustrates how trade-offs will need to be made to overcome the emerging challenges from non-techno-economic aspects to reach a timely energy transition.

Sammendrag

Det europeiske energisystemet er i rask endring med utfasing av fossil kraft og utbygging av vind- og solkraft som hovedkomponenter. Dette har medført utslippsreduksjoner i kraftsektoren, men for å nå klimamålene kreves det sterkere innsats også i andre sektorer. Direkte elektrifisering basert på fornybar kraft kan potensielt bidra til utslippskutt i andre sektorer som oppvarming og transport. Med en slik utvikling vil fremtidig etterspørsel etter elektrisitet vokse, og utbygging av mer fornybar kraft vil være nødvendig. Økende karbonpriser og synkende kostnader ved vind- og solteknologi bidrar til å bedre den økonomiske konkurranseevnen til fornybar energi mot fossilbasert kraftproduksjon. Den kraftige veksten i fornybar kraftproduksjonen skaper imidlertid nye utfordringer som ligger utenfor de teknoøkonomiske aspektene. Denne avhandlingen presenterer en gjennomgang av de nordiske kraftmarkedsutsiktene, etterfulgt av tre modellanalyser for å undersøke hvordan nye utfordringer knyttet til økende kraftbehov, fordelingsvirkninger og arealbruk kan påvirke fremtidige energisystemer.

En litteraturgjennomgang av langsiktige markedsanalyser for kraftmarkedet (Artikkel I) danner grunnlaget for tre modellanalyser som er gjennomført i denne avhandlingen. De langsiktige markedsanalysene bruker oftest energisystemmodeller, som består av tre nøkkelkomponenter: etterspørsel, tilbud og handel mellom regioner via kraftnett. Modellene legger til grunn tekno-økonomiske optimaliseringer ved kostnadsminimering eller maksimering av samfunnsøkonomisk overskudd. Litteraturgjennomgangen avdekker at det etterspørselssiden i kraftmarkedet har blitt behandlet mindre grundig enn tilbudssiden, og fokuset på sluttbrukssektorer for elektrisitet er som regel begrenset. På tilbudssiden peker analysene på at en kraftig økning av variabel fornybar kraftproduksjon er nødvendig, men utviklingen av landbasert vindkraft er i nyere studier begrenset tiltros for kostnadskonkurranseevnen og høye kraftpriser. En potensiell hindring for landbasert vindkraft er mangel på sosial aksept. De aller fleste analysene anser økt handel med kraft mellom land som en sentral del av energiomstillingen, men noen fremstår som mindre positive enn andre som følge av omfordeling av velferd. Basert på litteraturgjennomgangen omhandler de tre resterende studiene i avhandlingen (i) økt kraftbehov som følge av utslippskutt til oppvarming, (ii) fornybar kraft og (iii) økonomiske effekter og dilemmaer ved økt handel med kraft mellom land.

Artiklene II-IV videreutvikler og anvender energisystemmodellen Balmorel. Det vanlige Balmorel-rammeverket modellerer kraft- og fjernvarmesektorene i Nord-Europa. En ny

modul for den desentraliserte varmesektoren er utviklet i Artikkel II for å analysere varmesektorens innvirkning på kraftsektoren på lang sikt. Analysen viser at over 80% av behovet for romoppvarming og varmtvann i Nord- og Vest-Europa forsynes av desentraliserte varmesystemer, som i liten grad er avkarbonisert til tross for at det finnes eksisterende modne løsninger. Modell resultatene viser at elektrifisering gjennom varmepumper og hybridsystemer er de mest kostnadseffektive løsningene for å oppnå full avkarbonisering. Forutsatt et fremtidig varmebehov som tilsvarer dagens behov, vil avkarbonisering av varmesektoren i Nord-Europa kreve 700 TWh ekstra fossilfri elektrisitet. Ifølge resultatene i artikkel II vil dette bidra til en femdobling av installert vindkapasitet og det øker kraftbehovet i vinterhalvåret betraktelig. Artikkel II demonstrerer viktigheten av å koble kraft- og ikke-kraftsektorene i analysene for dekarbonisering.

De to siste artiklene (III og IV) innlemmer ikke-teknoøkonomiske perspektivene i Balmorel-modellen for å vurdere deres innflytelse på energiovergangen. En ulempe med fornybar kraft er at produksjonen krever større arealer enn fossile alternativer. Arealbehov adresseres som regel ikke eksplisitt i teknoøkonomiske optimaliseringsmodeller som Balmorel. Artikkel III anvender konseptet modelling to generate alternatives på Balmorel for å søke etter løsninger for det fremtidige energisystemet som er nær økonomisk optimale, men som forårsaker mindre arealbrukskonflikter. Resultatene viser at det økonomisk optimale utslippsfrie kraftsystemet vil kreve fire ganger så mye areal som i dag til energiproduksjon. Arealbruken kan reduseres ved å erstatte landbasert vind- og solkraft med mer offshore vind- og kjernekraft, men kostnadene for å utvikle et utslippsfritt energisystem vil da øke. De estimerte impliserte årlige kostnadene for å unngå fornybar energiproduksjon på land varierer fra €200 k/km^2 til €700 k/km^2. Disse arealverdiene er betydelig høyere enn markedsprisene for tilsvarende arealer i dag.

Artikkel IV presenterer en scenarioanalyse for å kvantifisere de økonomiske potensialene ved kraftutveksling mellom land i Nord Europa. Vi sammenligner et scenario med optimal overføringskapasitet - ved minimering av systemkostnad - med et annet scenario med gitt overføringskapasitet og uten utvidelse etter 2030. Ifølge resultatene bidrar økt handelskapasitet mellom land til lavere systemkostnader og reduserte utslipp. Med våre forutsetninger finner vi at en økning på i alt 76 GW overføringskapasitet mellom land i nord europa kan redusere systemkostnadene med 5%. Dette vil redusere $CO2$-utslippene med 40 % mellom 2030 og 2050, sammenlignet med scenarioet uten flere mellomlandsforbindelser. Vind- og vannkraftprodusenter i Norden tjener mest på økt handel over landegrensene, samtidig som inntjeningen økes med 67% ifølge modellresultatene. En annen effekt er at nordiske forbrukerkostnader for elektrisitet også øker med 21%. Økte forbrukerkostnader i eksportregioner kan bidra til betydelig motstand mot økt utvekslingskapasitet mellom land.

Denne avhandlingen viser, det store behovet for fornybar elektrisitetsproduksjon som vil kreves i for å omstille til et mer klimavennlig energisystem – og dette er i tråd tidligere litteratur. I tillegg viser avhandling til nye viktige avveininger vi står overfor i omstillingen til et klimavennlig energisystem.

Synopsis

1 Introduction

1.1 The energy transition in Northern Europe

Combating climate change has become a global consensus, of which the energy sector is at the centre. Over the past decade, renewable energy deployment has increased, and the costs of wind and solar power generation have declined substantially. Levelised costs of electricity (LCOE) from PV declined by 85%, onshore wind by 56% and offshore wind by 48% between 2010 and 2020, and the reduction trends will likely continue (IRENA, 2016; IRENA, 2021). Furthermore, carbon taxes and quota markets have been introduced nationally and internationally to internalise the costs of greenhouse gas (GHG) emissions for fossil-based producers. In recent years, auction prices for solar PV and onshore wind projects have become cost competitive with fossil-based generation (Figure 1). Transition towards a low-carbon energy sector is not only driven by policies but also by gaining strong economic motives.

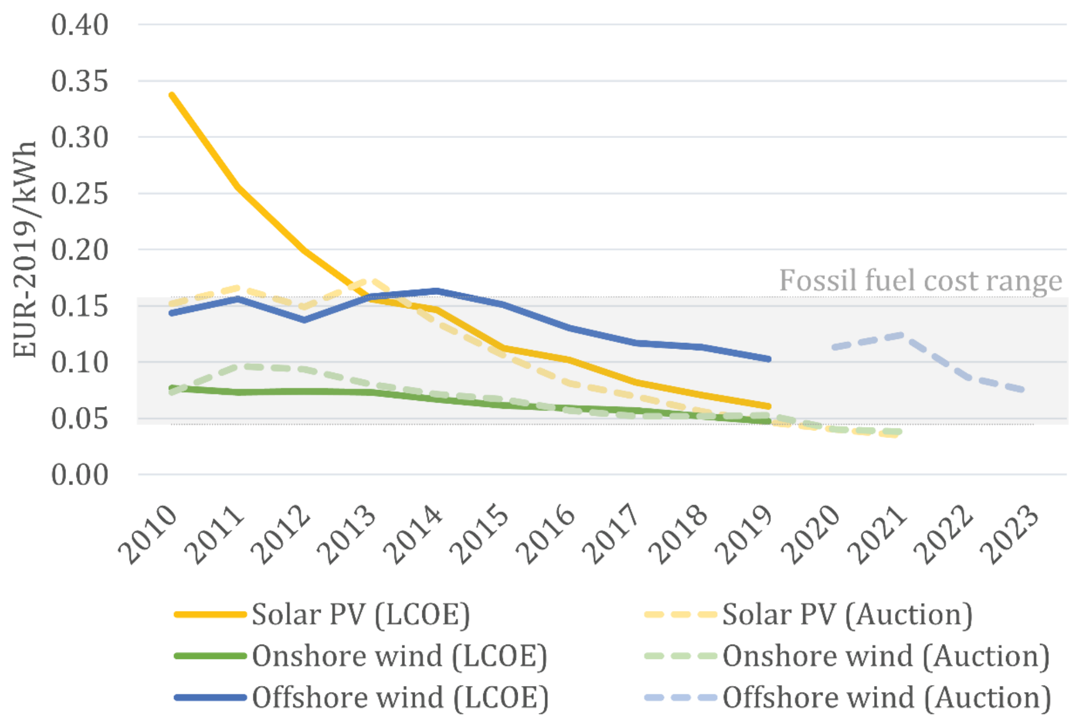

Figure 1. Weighted average costs of solar PV, onshore wind and offshore wind in the IRENA Renewable Cost Database. The grey band represents the range of fossil fuel-based power generation costs. Source: IRENA.

Renewables have become important sources of energy in Europe. In addition to the substitution of carbon-intensive generation, renewables also need to fill the gaps for nuclear power discontinuation in several countries. Shares of renewable electricity generation have doubled over the past decade. Wind power tripled its generation and became the biggest renewable electricity provider, and solar power generation grew rapidly from only 7.4 TWh in 2008 to 123 TWh in 2018. Consequently, CO_2 emissions from electricity and heat producers in Europe dropped 28% from 2008 to 2018 (IEA, 2021), and the overall share of renewables in the EU reached 20%, meeting its 2020 climate targets. In response to the observed progress and climate urgency, the EU has strengthened its 2030 climate targets and proposed the EU Green Deal, laying foundations towards the 2050 goal of carbon neutrality (European Commission, 2019a). Further efforts to expand the speed and scope of decarbonisation will be required in the coming decades.

Northern European countries are front runners in achieving low carbon energy systems. Renewable shares in the Nordics already reached 73% in electricity and 40% in overall energy consumption by 2018. The region has abundant hydro and bioenergy resources and great potential for wind power development. Wind energy has contributed to the major increase in electricity renewable shares; thus, providing flexibility to balance demand and variable renewable generation is one of the current challenges (Bird et al., 2016; Huber et al., 2014; Impram et al., 2020). Traditionally, hydropower in Norway and Sweden and district heating systems with combined heat and power (CHP) plants in Sweden and Denmark support system flexibility. Besides regulating supply and demand, system flexibility can also be provided via relocating the energy temporally through storage or spatially through power transmission. The current costs of battery storage are still high, although downward trends are expected (IRENA, 2017). Increased transmission levels are especially relevant to Northern Europe. Besides increasing system flexibility, these increased levels enable the Nordics to share the renewable resources with neighbouring countries, such as Germany and the UK, where the scales of energy systems are much larger. Such cooperation is beneficial to efficient decarbonisation.

The need for renewable electricity might exceed the previous estimation. Around 60% of CO_2 emissions in Europe in 2018 were from other non-power sectors, such as transport, heating and industry. Compared to the power sector, they have shown little mitigation progress. With rising renewable shares, electricity is becoming an important source of clean fuel for other sectors. New challenges will emerge in the coming phase of the energy transition, which requires substantial renewable deployment to ensure a clean, secure, and affordable supply of energy. The goal of this thesis is to provide insights for constructive discussions to proceed further towards a low carbon future.

1.2 Research scope and objectives

1.2.1 Scope of the energy transition in this thesis

The scope of the energy transition in this thesis refers to the transformation of energy systems towards low or zero carbon by 2050. Rosenbloom (2017) proposed three core dimensions, including biophysical, techno-economic and socio-technical, in low-carbon transition pathways, and this thesis focuses on the techno-economic dimension, linking the current system to the future. The inertia in the techno-economic dimension follows neoclassic economic assumptions and emphasises rational economic factors such as costs (Cherp et al., 2018; Rosenbloom, 2017).

Millot and Maïzi (2021) argue that drivers beyond economic interests are required for the transition to carbon neutrality. Multiple aspects are co-evolving in an energy transition (Foxon, 2011), and besides the techno-economic dimension, there are also social-technical and political perspectives to consider (Cherp et al., 2018). The social-technical perspective focuses on broader societal change, such as knowledge stocks and niches in energy technologies, technology lock-in and actors' behaviour. The political perspective focuses on change in political actions and policy interests. These dimensions are all interlinked.

The European energy transition has entered a 'breakthrough' phase (Rotmans et al., 2001), where variable renewable shares in electricity generation accelerate rapidly, and new research and policy focus is required (Markard, 2018). In this next phase of the energy transition, renewable energy technologies are getting mature, costs have declined and focus has turned to enhancing system and sectoral integration. Energy transition research must take into account new challenges, such as escalating struggles due to conflicting interests and social acceptability (Markard, 2018; Millot & Maïzi, 2021; Papadis & Tsatsaronis, 2020).

This thesis takes the techno-economic perspective to maximise social welfare as the dominating approach, and the main components of energy systems in this thesis are energy flows and markets. Many quantitative analyses have been conducted with energy system models, with detailed representations of energy flows, conversion processes and markets for balancing supply and demand. Figure 2 illustrates the scope of the analyses within this thesis. The figure shows an example of the structure of an energy system model, covering primary energy supply (the black block), demand (grey blocks), conversion technologies (green blocks), energy flows (arrows) and examples of input constraints and outputs (arrow blocks). Although not explicitly analysed, the non-techno-economic perspectives (social-technical and political) are embedded in the given assumptions. Challenges in the non-techno-economic perspectives and how they affect energy flows of demand and supply and cross-border interconnection are prioritised in this thesis. This approach encapsulates the technical complexity in energy systems and delivers the equilibrium electricity prices, which are important information for timely low-carbon transition to policymakers and society (Markard, 2018; Papadis & Tsatsaronis, 2020).

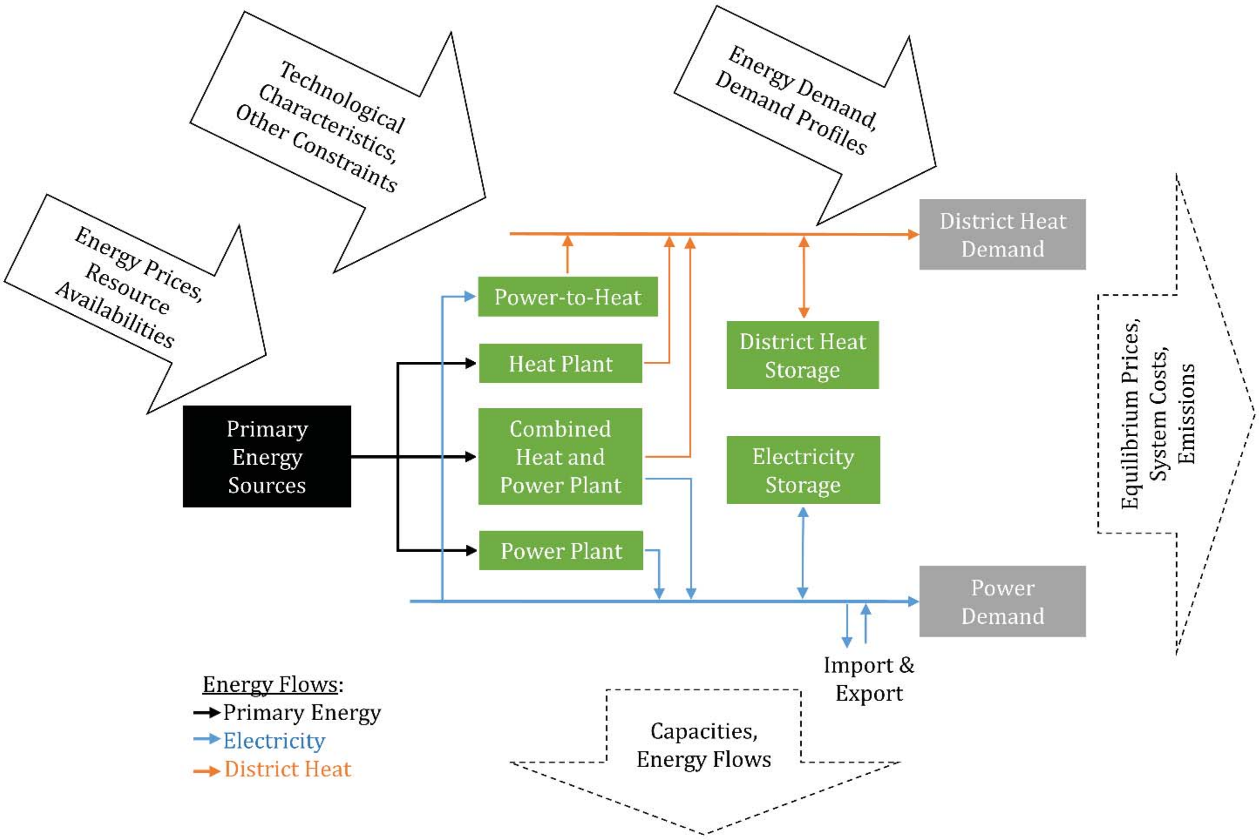

Figure 2. Illustration of the components (blocks), inputs (block arrows) and outputs (block arrows with dash outlines) of an energy system model.

1.2.2 Perspectives in long-term power markets

Affordable, reliable and low-carbon electricity plays a crucial role in the energy transition. Power market outlooks reflect the perspectives of their publishers, and these materials serve an important role in energy planning and investment decision making. To identify the main challenges transiting from current to a low-carbon energy system, we have conducted a thorough review of recent Nordic power market outlooks. Several Nordic power market stakeholders publish market outlooks regularly, and a holistic review reveals which, and in what way, these materials address the challenges. In total, we have reviewed 43 scenarios in 15 power market outlooks published by Nordic transmission system operators, regulators and research institutes between 2016 and 2019. See Paper I for the full list and lessons learned. Based on the review, we have identified potential improvements in sectoral coverage and the need for further investigation of non-techno-economic aspects in the energy transition. The following paragraphs summarise some of the key findings from the demand, supply and cross-border interconnection aspects.

- Demand

Electricity demand is an important factor to the scale of a power system. Traditionally, electricity demand is considered inflexible, and power balance relies more on supply-side operations. Thus, the energy system models applied in these market outlooks generally had more detailed descriptions on the supply side than on the demand side. It was common practice to simplify demand development as constant, adjusted according to GPD and population projections, or downwards, based on the assumptions of efficiency improvement. In the very recent years, the demand side has received more attention. On the one hand, growing shares of variable renewable energy (VRE) lowers supply-side flexibility; on the other hand, further decarbonisation benefits from coupling different energy sectors, which enhances demand-side flexibility. Nonetheless, among the reviewed outlooks, only the Swedish energy agency explicitly analyses a high electrification scenario (Energimyndigheten, 2019). In this scenario, the electricity consumption will increase by 38% from 2020 to 2050, resulting from the electrification in heating, transport and industry sectors. The high fuel and emission price scenario (Hög) in the outlook from Svenska Kraftnät (Brunge et al., 2019) shows 26% growth in electricity consumption from 2020 to 2040, and it assumes that the new industry sector, including data centres and battery factories, contributes the most. Overall, future electricity consumption in rest of the reviewed scenarios is simplified and potentially underestimated. (Figure 3).

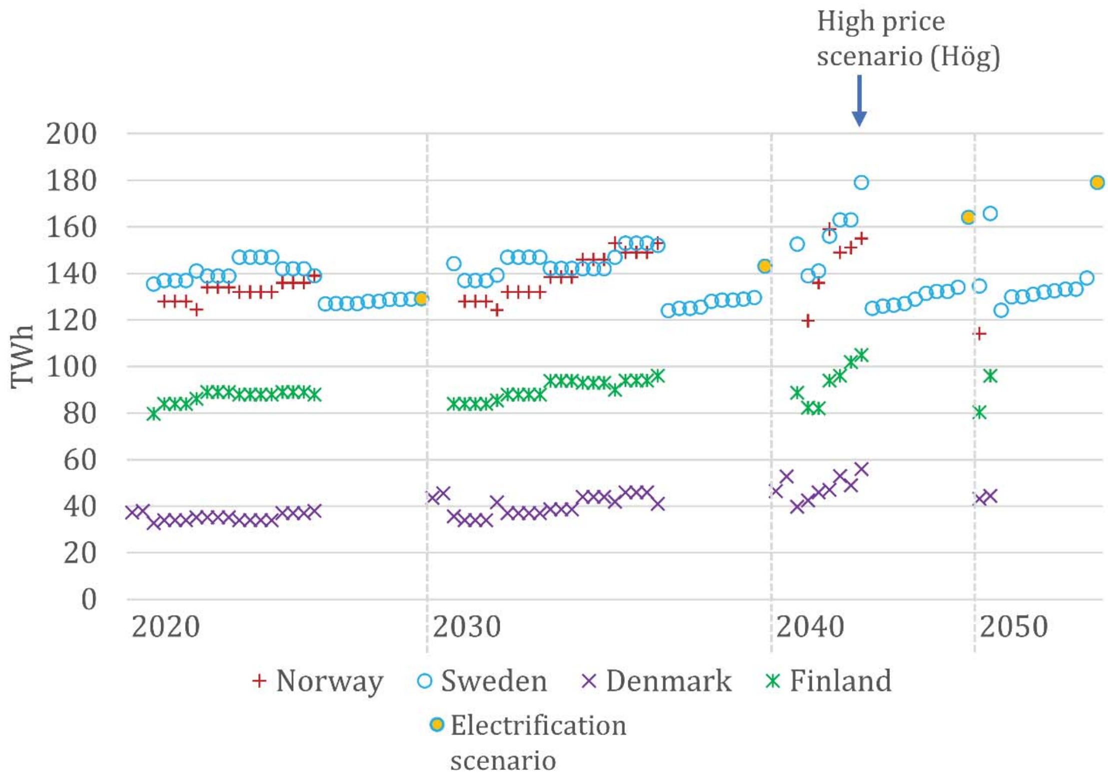

Figure 3. Electricity consumption from the reviewed outlooks in Paper I. Each column represents one scenario.

- Supply

The reviewed outlooks generally shows that Northern Europe will gradually phase out coal and limit nuclear power, and steadily increase their VRE shares in the electricity mix towards 2050. There are two types of approaches in the reviewed outlooks to estimate future installed capacities – exogenously defined assumptions or a mixture of input assumptions and output results. Most reviewed outlooks apply the former approach, which might fail to capture the long-term dynamics of price signals and investment decisions. The latter approach reflects a market that is closer to perfect than the former, but it might underestimate the impact of the non-economic factors, such as policy and social acceptance.

Overall, regardless the approach, the reviewed outlooks show increasing wind deployment, and the newer outlooks often modify the future installed wind capacity upwards from their previous versions. The reviewed outlooks agree that onshore wind power does not require policy support. Despite the low costs of onshore wind, there is a tendency of more emphasis on offshore than in onshore wind in the newer outlooks. The Danish transmission system operator (TSO), Energinet, updated their assumptions to assign more increase in nearshore wind and less increase in onshore wind due to declining offshore costs and increasing local opposition (Energinet, 2017). The Swedish TSO, Svenska Kraft, included additional scenarios to investigate the effect of large-scale offshore wind expansion in the southern part of Sweden (Brunge et al., 2019). The Norwegian TSO, Statnett, and regulator, NVE (Norges vassdrags-og energidirektorat), regard future wind energy development in Norway more uncertain than in the other Nordic countries, and the latest publication mentions particularly the "encroachment on nature" (*naturinngrep* in Norwegian) as one major factor to restrict the onshore wind development (Gogia et al., 2019).

Power price outlooks are important indicators for capacity expansion investments, and the reviewed scenarios suggested that power prices after 2040 might be more than 40 or 50 €/MWh, as a result of the assumptions of growing fuel and emission quota prices. This price level will be beyond the long-run marginal costs of onshore wind in the Nordics – around 30-35 €/MWh in Norway (Bøhnsdalen et al., 2018) and 37-56 €/MWh in Sweden (Energimyndigheten, 2019). The self-cannibalisation effect of wind energy maybe be one explanation of the mismatch, or it might suggest that there are non-techno-economic factors impacting future generation capacity.

- Cross-border interconnection

Cross-border interconnection plays an important role in Northern European power markets. National energy systems are interlinked with neighbouring countries through physical transmission lines and integrated power. The reviewed Nordic outlooks included dedicated sections to describe energy system development in Continental Europe, which indirectly affects the Nordics through transmission lines. By connecting to larger markets, Nordic wind resources can assist the energy transition in Europe. Nordic hydro resources could also become the "battery" for Europe and overcome the flexibility challenges of VRE integration. All reviewed outlooks agreed on the need for power transmission, with slightly different statements. Outlooks from Dansk Energi emphasised the importance of transmission to Denmark with a section title "Denmark is not an island" (*Danmark er ikke en ø* in Danish) in its 2018 and 2019 outlooks (Capion et al., 2018, p.10; Poulsen et al., 2019, p.12). Its 2019 outlook allowed for transmission investment in the Blue and Green scenarios and stated that transmission connections would contribute to lower electricity prices and backup needs. Outlooks from Statnett, Svenska Kraft and the Norwegian regulator NVE (Norges vassdrags-og energidirektorat) adopted more conservative views for transmission and did not consider new connections that were not under construction. Statnett and Svenska Kraft argued that market outlooks should acknowledge the need for more power transmissions, but not intend to signal further grid development without a more thorough analysis. NVE stated that Norway would experience larger price variations by being more connected to Europe by 2030, but further development beyond that would be quite uncertain. These findings suggest that increased international electricity trade will bring overall welfare in the energy transition but might encounter barriers due to unevenly distributed benefits among the stakeholders.

1.2.3 Research objectives

Taking into account the identified barriers and gaps in the literature, the main research objective of this thesis is as follows:

> *To investigate the emerging challenges in the energy transition and their roles in shaping the future Northern European energy systems.*

Some of the findings in Paper I, which reflect the perspectives of power market stakeholders, form the basis of the sub-objectives. In the demand aspect, the focus is narrowed down to decentralised heating, which takes large shares in final energy use in Northern Europe, but is yet to be decarbonised. In the supply and cross-border interconnection aspects, we focus on non-techno-economic barriers. Bolwig et al. (2020) has summarised the challenges faced by onshore wind and power transmission in Northern Europe from the social-technical perspective. Despite their climate friendliness, the literature shows that these technologies are facing social opposition originating from concerns of health, impact on environment and landscape, and distributional effects. The following sub-objectives in each are thus defined to address the emerging challenges:

- To assess the impact of heating decarbonisation on the power sector by integrating decentralised heating into the centralised power and heat model.

- To analyse how prioritising avoiding land conflicts affects future energy systems and investigate alternative solutions.
- To quantify the impact of utilising the economic potential of cross-border transmission in future energy systems.

The sub-objectives are investigated through three modelling studies. Through the manuscripts and the sub-objectives, this thesis adds insight into the research field of energy system analysis and provides rational support in addressing emerging challenges in the energy transition.

2 Emerging Challenges in the Energy Transition

This section describes the background and literature review related to the sub-objectives under electricity demand and the decarbonisation of end-use sectors, renewable supply and land conflicts, and dilemmas in cross-border interconnection.

2.1 Demand: Decarbonisation beyond the power sector with clean electricity

Little mitigation progress has been observed in other energy sectors compared to electricity generation (European Commission, 2019b). CO_2 emissions from electricity and heat producers declined by 32% between 2008 and 2018, while those from residential, services, transport and industry decreased by only 10% during the same period (IEA, 2021). Most of these emissions are not covered by the EU's Emission Trading System (ETS). In 2018, 17% of the CO_2 emissions in the EU were from residential and services sectors, 29% from transport and 13% from industry (IEA, 2021). Legally binding national targets for 2030 are set for emissions from sectors outside of the ETS under the Effort Sharing Regulation (European Union, 2018), and stronger changes in the non-ETS sectors are expected in the coming decades.

Electricity from renewables is a promising mitigation strategy. A 2050 baseline scenario by PRIMES model analysis showed a strong increase in electricity demand, led by electrification in heating, cooling and transport, and an increase in demand in IT and leisure appliances, despite the decrease in total energy production (European Commission, 2018). In addition to increasing the overall scales of electricity demand, these sectors will most likely influence the electricity demand hourly profiles and peak loads (Kannan, 2018; Zeyen et al., 2021; Østergaard et al., 2015).

From the end use viewpoint, residential and services sectors take the highest share, around 40% of the final energy consumption in the EU, followed by 31% for transport and 25% for industry (IEA, 2021). The main energy need in residential and services sectors, especially in Northern Europe, is domestic heating, for which several decarbonisation solutions are mature. The transport and industry sectors require more advanced forms of energy, including petroleum products, synthetic fuels and high temperature heat, and those services are more challenging to decarbonise. It is our impression that many researchers focus on difficult topics, such as decarbonising transport and industry sectors. Nonetheless, decarbonising heating in residential and services sectors is a low hanging fruit with a lower techno-economic threshold than decarbonising other energy services in transport and industry sectors. The impact of heating decarbonisation on the overall energy system should not be overlooked considering the scale of demand.

Heating can be supplied by centralised district heating networks and decentralised individual heating systems. Centralised heating systems are relatively well-developed in Northern European countries. Except for Norway, 28% to 37% of the national final energy consumption in the residential sector in Northern Europe is from district heat, compared to the 8.5% average share in the EU in 2019 (Eurostat). That share is less than 7% in Germany, and less than 1% in the UK. While it is possible to expand the district heating system and shift from decentralised to centralised heating, the incentives are low with shrinking heat demand (Lygnerud, 2018). Much of the heat relies on decentralised heating systems, such as boilers, direct electric heating, stoves and furnaces, and heat pumps; however, these systems have been overlooked. As indicated in Paper I, only some of the models applied in the outlooks endogenously model district heat in addition to electricity. Decentralised heating tends to be simplified and embedded in the electricity demand assumption, if not ignored.

Electricity is regarded as the energy carrier that can be decarbonised first, and sector coupling and electrification are important solutions to decarbonise other sectors with decarbonised electricity (Gea-Bermúdez et al., 2021; Papadis & Tsatsaronis, 2020; Van Nuffel et al., 2018). Existing energy transition studies emphasise the benefits of system flexibility from coupling electricity and transport, gas and district heat (Helgeson & Peter, 2020; Jensen et al., 2020; Kavvadias et al., 2019; Thellufsen & Lund, 2017), and recent literature has started to integrate decentralised heating into the analysis (Brown et al., 2018; Gea-Bermúdez et al., 2021; Kavvadias et al., 2019). It is important to retain the characteristics of decentralised systems, such as individual preferences (Li et al., 2018) and limited long-term storage, as they might affect the energy system in different ways. Paper II expands the scope of the demand side in energy system modelling to cover the decentralised heat and assesses the impact on the energy system for reaching the long-term mitigation targets.

2.2 Supply: Gaps between wind energy potential and social acceptance

Wind and solar energy play key roles in a low-carbon future. In Northern Europe, wind energy has a more advantageous seasonal generation profile than solar energy, with more winter production than summer, in line with seasonal demand patterns (Holttinen, 2005). Surveys in the early 2000s showed high public support of wind power in Europe (EWEA, 2003), and countries have implemented policy frameworks to attract investments. Through technology learning and economies of scale, onshore wind energy technologies have become increasingly cost competitive, as mentioned in Section 1.1.

One disadvantage of wind energy is the low installed capacity density. The wind capacity density is affected by the physical requirements for wind turbines and the wind farm layout. The amount of power that can be harvested by a wind turbine is calculated as follows:

$$\frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 \times \eta,$$

where ρ is the air density, v is the wind speed, d is the turbine diameter and η is the efficiency factor. The best efficiency factor of a turbine is 16/27 under the Betz limit. The power density is derived by dividing the above equation by the surface area, which depends on the layout design of a wind farm. Assuming a simple square layout where turbines are placed with a spacing distance five times the turbine diameter, air density of 1.3 kg/m^3, a rated wind speed of 12 m/s, and an efficiency of 0.5, the installed capacity density is 17.6 W/m^2, which is equivalent to 0.057 km^2 per MW installed. This is a simple estimation, and a wide range of wind capacity densities have been reported – 1.5-20.5 MW/km^2 for onshore wind and 3-12 MW/km^2 for offshore wind – depending on the assumptions of turbine design, layout and the definitions of a wind farm area (Enevoldsen & Jacobson, 2021). Solar energy also has low installed capacity density, but the land impact issue is less severe.

Typical installed capacity density assumptions of solar PVs range from 85 MW/km^2 on rooftops to 300 MW/km^2 in open fields (Ruiz et al., 2019). Among wind, solar and hydro energy, wind energy is perceived as the most negative and has the biggest landscape and visibility impact (Ioannidis & Koutsoyiannis, 2020).

The total installable wind capacity can be estimated by the installed capacity density multiplied by the eligible areas. Areas of cultural or natural importance and areas close to infrastructures or buildings are restricted for wind projects. Besides weather conditions, accessibility to grid connections, terrain and land rents are some of the local factors to consider in wind energy development (Ryberg et al., 2019). Owing to different assumptions of installed capacity density, criteria of suitable areas for wind energy, wind conditions, and social and political ambience, a wide range of onshore wind potential estimates is found in the literature (Child et al., 2019; Enevoldsen et al., 2019; Osorio et al., 2020; Ruiz et al., 2019; Ryberg et al., 2019). Figure 4 and Table 1 summarise the definitions and levels of onshore wind potential estimations by country in recent literature. Overall, the existing literature shows that there is sufficient onshore wind potential for the energy transition, especially in the Nordic countries.

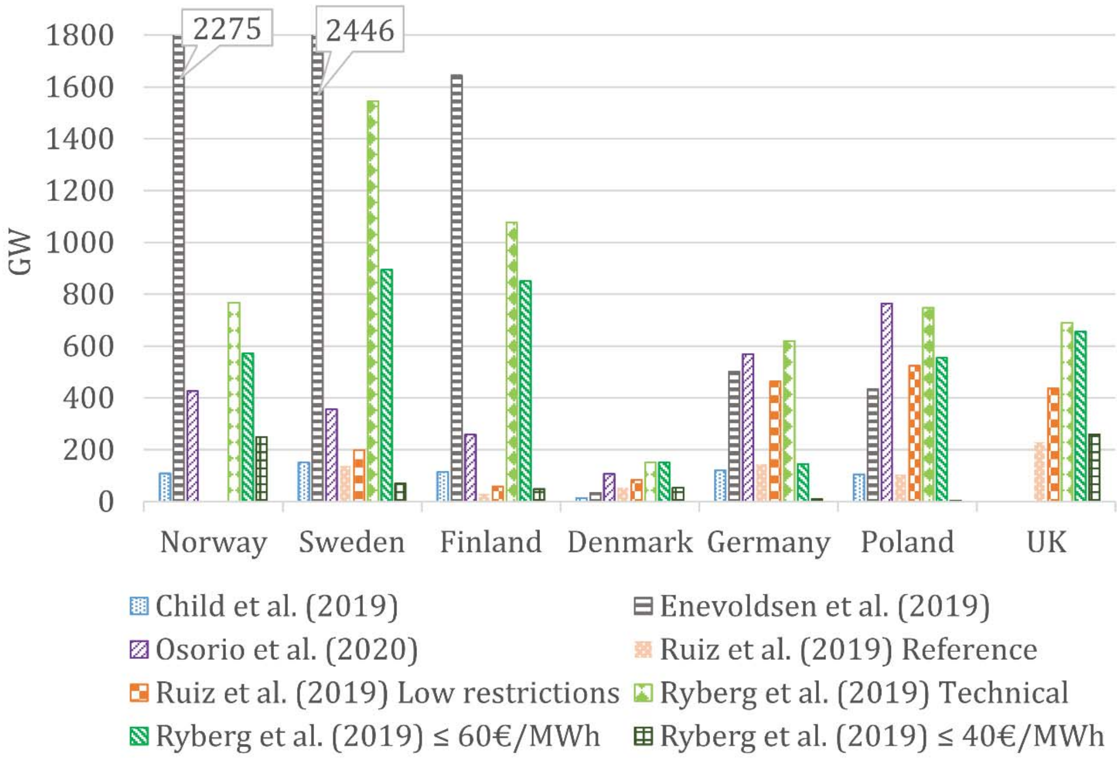

Figure 4. Onshore wind installed capacity potential by country in existing literature.

Table 1. Lists of onshore wind installed capacity density and the definitions of potentials in literature.

Literature	Capacity density (MW/km^2)	Potential definition
Child et al. (2019)	8.4	4% of the total territory assumed eligible for onshore wind.
Enevoldsen et al. (2019)	10.7	Exclusion zones by own assumptions of setback distances from infrastructure, buildings and protected areas.
Osorio et al. (2020)	5	Area within 80 km to nearest large load or power plants, excluding protected, urban and high-elevation areas, or certain land cover types.
Ruiz et al. (2019)	5	Reference scenario: Current legal requirements for exclusion zones and setback distances. EU-wide low restrictions: A hypothetical scenario in which the exclusion of surfaces for wind converges in all countries to 400 m.
Ryberg et al. (2019).	9.9	Technical potential: own assumptions of land eligibility, taking into account turbine placement and site-specific designs. Two cost levels filtering economic limitation.

Public perceptions can vary over time, space, roles, and personal experience (Dugstad et al., 2020; Mytilinou et al., 2017; Warren et al., 2005), and in recent years the social acceptance of onshore wind has become less optimistic. Large scale deployment raises concerns about land competition with agriculture, human activities, wildlife protection and preservation of nature landscapes (Bolwig et al., 2020). Concerns for land conflicts have become a barrier for onshore wind development (Palmer-Wilson et al., 2019). According to an expert survey by Suškevičs et al. (2019), 'encroachment into the landscape' is the strongest resistance factor in Northern and Western Europe against wind energy. A survey in Norway showed a significant decrease of positive public perceptions of onshore wind from 84% in 2011 to only 36% in 2020 (Livgard, 2020). The lack of acceptance can lead to delays or rejections of planned projects, and in 2021, the director of Norwegian regulator (NVE) acknowledged that it is unlikely to see strong development in onshore wind in Norway in the next decade (Amundsen, 2021). Social acceptance and public concerns are becoming decisive for future onshore wind deployment.

Perspectives of wind energy affect energy transition pathways. Most of the power market outlooks reviewed in Paper I regard future wind deployment as input assumptions, and market mechanisms for wind energy investments are omitted. By contrast, future wind deployment can also be an output result generated by an energy system optimisation model. The assumptions of wind energy potential and costs are important under this approach, as the optimisation will land on the most cost-effective solution until reaching the potential constraints. Recent observations have shown that future wind deployment will likely be constrained by lack of social acceptance long before exhausting the potential, and it may lead to cost increase and consequently shift generation towards more local or costly solutions (Bolwig et al., 2020). In Paper III, we first quantify the land requirement in the least-cost solution. Instead of targeting wind energy directly, we explore alternative solutions that minimise land conflict concerns with little cost increase.

High shares of wind energy also introduce challenges in energy systems and market integration. The variable generation of wind increases the need for system flexibility to ensure energy security. The inflexible generation of wind cannibalises its market value. Paper IV focuses on the potential of increased interconnection, which provides system flexibility and mitigates parts of the wind market value cannibalisation by offering the supply to larger markets.

2.3 Cross-border interconnection: Overall benefits hindered by distributional effects

Electricity interconnection brings socio-economic values through enhancing the efficiency of electricity systems, security of supply and job creation. The EU has set targets under its climate and energy framework to promote cross-border transmission, aiming at transmission capacities that enable sending 10% of the national generation abroad by 2020 and 15% by 2030 (European Commission, 2015; European Commission, 2017). Existing literature has shown the benefits of electricity interconnection in cost reduction, reducing the need for backup power, system adequacy and renewable integration (Becker et al., 2014; Cao et al., 2021; Directorate-General for Energy, 2019; Rodríguez et al., 2014; Schlachtberger et al., 2017). Child et al. (2019) claim that interconnection is especially relied upon by areas with rich wind, solar or hydropower resources and areas with high demand. Northern Europe, with its well-integrated power markets, good wind conditions and abundant hydro resources, has seemingly good prerequisites for cross-border cooperation through increased interconnection.

Cross-border interconnection is nonetheless facing increasing challenges. Besides concerns originating from physical electric cables causing health, visual and environmental impact, some concerns originate from shared electricity markets. As shown by the different attitudes of various power market stakeholders in Paper I, although increased market cooperation plays an overall positive role in the energy transition, some might benefit more than others, and some might be worse off. Figure 5 illustrates the merit order effect of connecting two electricity markets. Market A represents a high price (P_A) area with large demand and limited VRE generation, and market B represents a low price (P_B) area with lower demand and more VRE generation. When the two markets are connected by transmission lines, power can flow until the two markets reach the same market clearing price, or until power flow reaches the bottleneck, constrained by the transmission capacity. In Figure 5, the consumers in market A benefit from the price drop to P^*_A thanks to the imported low-cost power from market B. In market B, it is the producers, especially the VRE producers, that receive higher revenues as the market clearing price increases to P^*_B, but the consumers also have to pay higher prices. The transmission grid owner profits from the price differences (P^*_A - P^*_B) multiplied by the exchanged power flows. Depending on the roles in power markets, cross-border power transmission is more welcomed by some than others.

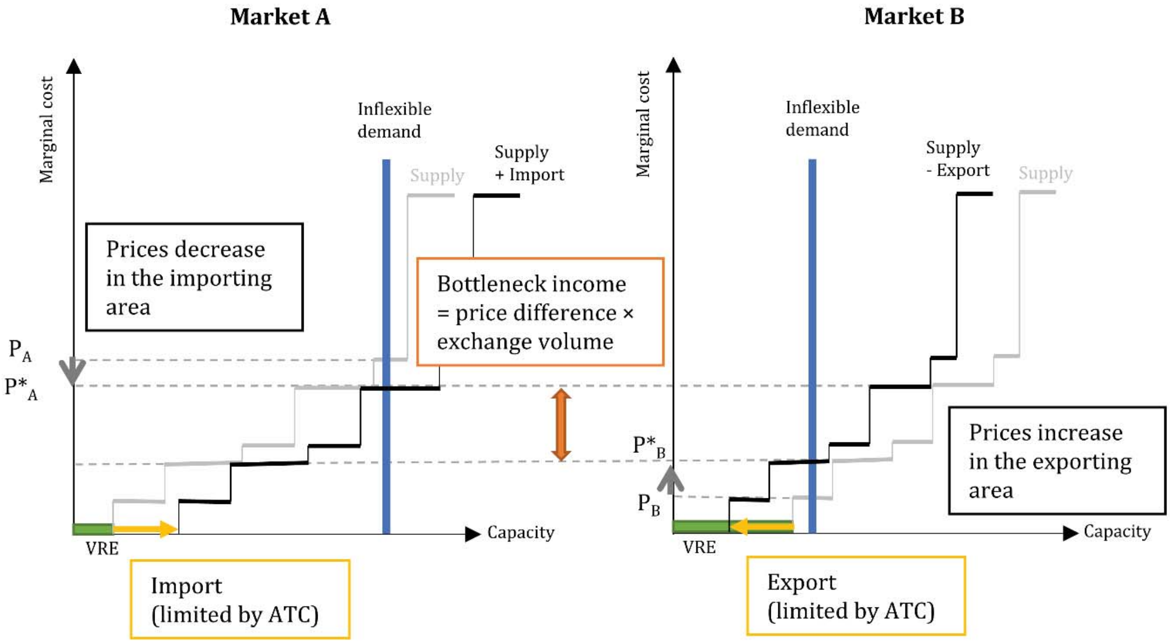

Figure 5. Illustration of power market effect of interconnection two markets, where the transmission volume is limited by the available transfer capacity (ATC).

The geographical and sectoral welfare redistribution causes challenges in promoting interconnecting the electricity markets in different countries. For example, the NorthConnect project, listed as one of the EU's 'Projects of Common Interest' linking Norway and Scotland, caused fear of raising electricity prices for household and industry consumers and was put on hold by the Norwegian government.

Notably, whether a market is an importer or exporter is fluid, especially with increasing shares of renewables. The market clearing prices depend on the residual demand, that is how much demand is left after subtracting the must-run units and the VRE generation, which is affected by weather conditions. Take Norway as an example of a typical net exporting country with abundant hydropower. Figure 6 shows the hydropower production, net export and spot prices in Norway between 2009 and 2019. In most years, Norway was a net exporting country with electricity prices of less than 30 øre/kWh. This was not the case in 2010, a cold and dry year. Hydropower produced less than usual, and Norway had to import more than it exported, with the spot price reaching over 45 øre/kWh. This example shows that no market participant is always only benefiting or losing from cross-border interconnection. Such cooperation enforces weather resilience and offers long-term flexibility, which is much needed under the impact of climate change.

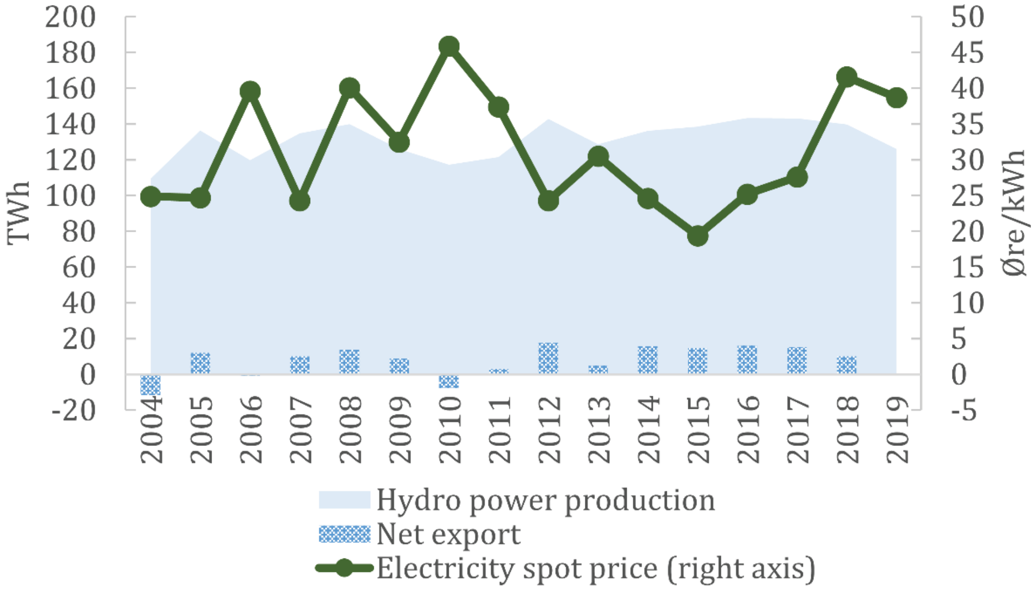

Figure 6. Hydropower power production, net export, and spot prices in Norway from 2009 to 2019. Source: Statistics Norway

Without sufficient cross-border interconnection in energy systems, the process of the energy transition will be slower and more burdensome. Schlachtberger et al. (2017) demonstrate the benefits of highly interconnected electricity grids in a low-carbon Europe, where onshore wind becomes the main source of electricity. However, if the possibility of utilising interconnection is restricted, the system shifts towards more solar power plus storage and overall costs and emissions increase (Cao et al., 2021; Schlachtberger et al., 2017). Limiting transmission expansions adds disadvantages to wind development (Bolwig et al., 2020; Neumann & Brown, 2021). Paper IV focuses on the benefits and costs brought about by cross-border transmission in power markets, and it aims to provide quantified support for addressing the welfare distribution challenge.

3 Methods

3.1 Energy system modelling

Energy system models are quantification tools for analysing complex problems in the energy sector. System boundaries are drawn, within which the real world is simplified and expressed by equations and parameters. The need for complex energy system models increases in response to addressing the increasing complexities of issues involving multiple aspects. Different models and model topologies have been developed and proposed, and following the logic proposed by Després et al. (2015) and Ringkjøb et al. (2018), the following criteria are identified for the modelling tool to be used for the research objective in this thesis:

- Purpose: Investment decision support, Scenario

The thesis investigates how future energy systems might be shaped and the model must provide investment decision support for energy infrastructure, including generation, storage and transmission technologies. The installed capacities of technologies are modelling outputs reflecting various scenarios of the energy transition.

- Point of view: system approach

The research topic is addressed from a system viewpoint, in opposition to private actors' interests. Climate change is a global problem, and thus the modelling tool takes a central planner's perspective. An optimal solution is found when the total system costs are minimised. The society as a whole benefits, although it might not be in the best interest of some private actors.

- Approach: partial equilibrium and bottom up

Power markets provide important signals to energy sector investors, and thus the model is expected to focus primarily on the power markets and to show power market data, such as day-ahead prices. A partial equilibrium approach is applied, while the rest of the economy is not modelled. A bottom-up (or hybrid) approach is desired to describe adequate technological details in the system.

- Represented energies: electricity and heat

The model must be able to capture the interactions between electricity and district heat. District heating systems are common in urban areas in Northern Europe, and they couple power systems through CHP plants and power to heat technologies. Coverages of other energy forms are additional benefits.

- Spatiotemporal resolution

The spatial resolution should be at least at the country level and preferably reflect the system bottlenecks, such as the price regions in Nord Pool. The research objective requires long-term analyses up to 2030 or 2050, and hourly resolution is preferred for day-head markets with high VRE shares.

- Support of open research

This thesis supports an open research spirit. An open-source model is beneficial to the science community for continuous development. Transparency is crucial to the interpretation and communication of analysis results.

Meeting all the above-mentioned criteria, the Balmorel model is applied for the analyses in this thesis. Modelling tools with the first three characteristics are often referred to as energy system optimisation models (ESOMs), which generate results of future energy systems, including installed capacities, utilisation, costs and emissions. The Balmorel energy system model is suitable for this thesis; it has been widely used in Northern European energy system studies and contains rich background data through continuous development since its first release (Wiese et al., 2018).

The Balmorel model describes Northern European power and heat systems with a bottom-up approach using partial equilibriums and assumes perfect competition in liberalised power markets. The model is formulated in linear programming (or mixed integer programming in some studies). The model is designed to have flexible settings, and new features and versions are continuously developed, which are available on the Github repository (The Balmorel Open Source Project). Balmorel, written in the General Algebraic

Modelling System (GAMS) language, is programmed to minimise the total system costs under a set of constraints. The objective function is defined by annualised investment costs of endogenously invested technologies, annual fixed and variable operation and maintenance costs, fuel costs and other costs such as taxes and grid tariffs in some cases. Energy balance equations are the most important constraints, which require electricity and heat demand, assumed inelastic in this thesis, to be met through the generation, loading and unloading of the storage technologies, or energy flow exchange at all times. The electricity and heat prices are obtained by the marginal values of the balance equations. Other important equations include equations describing energy transformation processes and resource availabilities. A thorough introduction of the model can be found in Wiese et al. (2018) and the papers included in this thesis.

3.2 Model development in this thesis

The model, including the framework and data, has been developed and updated continuously throughout the research period. The model versions and settings differ from one paper to another. As part of the thesis, new features are developed for the models applied in Paper II (decentralised heating) and Paper III (MGA technique). The model applied in Paper IV is based on the version that includes a new method of transmission modelling, developed during the research project Flex4RES, which focuses on the flexibility challenge in a renewable rich system (Nordic Energy Research).

3.2.1 Decentralised heating

To evaluate the influence of a fully decarbonised heating sector, the Balmorel model is expanded to include additional energy forms of decentralised heat in the residential and commercial sectors. The industrial heat demand is not included because it often has high and/or specific temperature requirements. Two new types of energy demand, space heat and hot water, have to be met, respectively, and their model structures form in parallel to the electricity and district heat sectors (Figure 7).

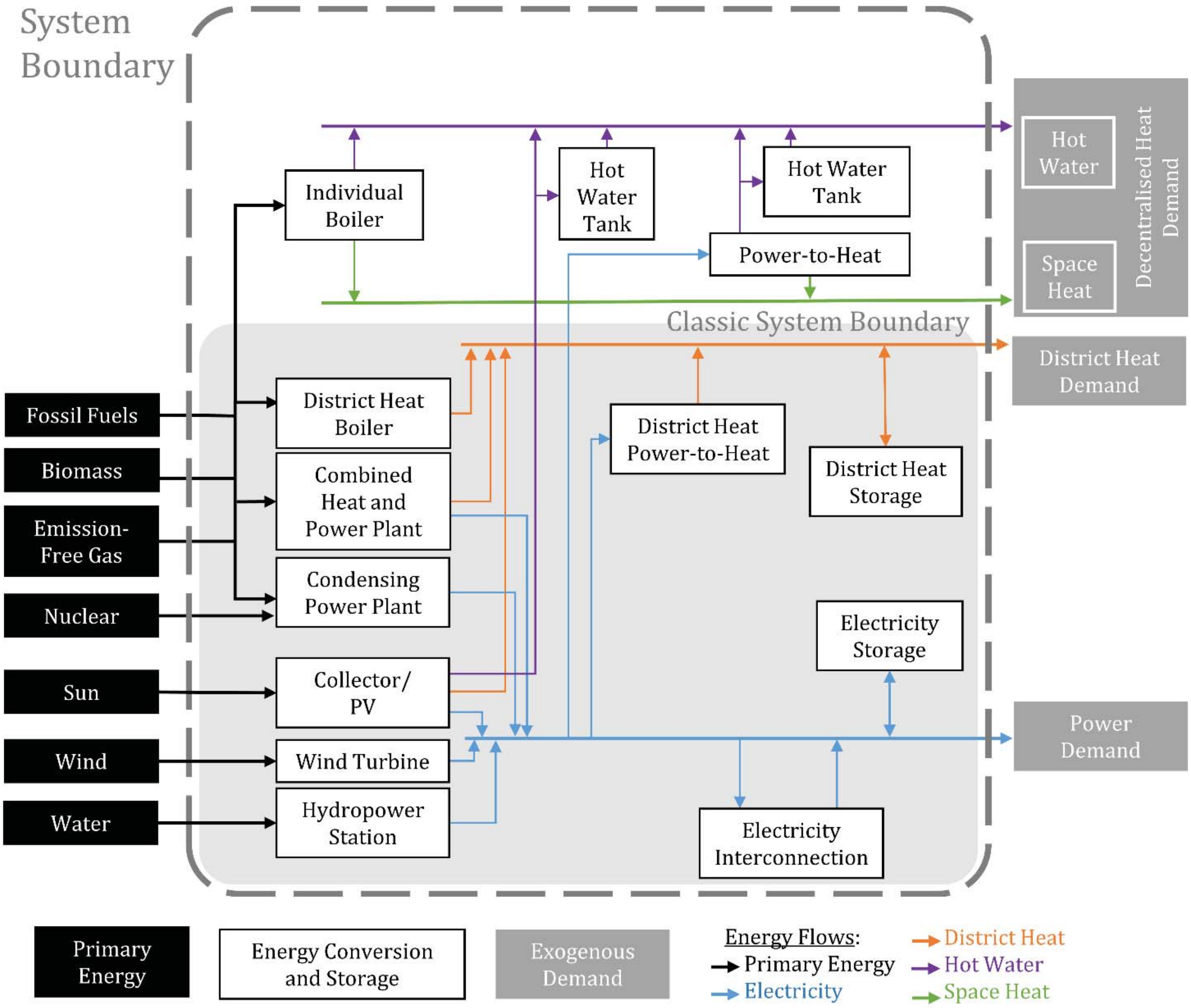

Figure 7. Illustration of the Balmorel model structure adding decentralised heating.

A top-down approach is applied in the decentralised heating sector. The residential and commercial consumers are aggregated by given sets of heating technologies, which include single or hybrid solutions of various types of boilers, solar heating, electric heating or heat pumps. The decentralised heating sector is coupled with the electricity sector through electric heating and heat pumps. No interaction between the centralised and decentralised heat sectors is modelled based on the assumption of limited district heating expansion in the modelling countries. Maximum rates of technology shift every decade are applied to presume the heterogenous willingness to shift among consumers. Within the shifting rates, decentralised heating consumers opt for heating solutions that achieve the least system costs. Measures of building efficiency improvement are considered exogenously, and scenarios with various heating demand developments are analysed. Further methodology and data description can be found in Paper II.

3.2.2 MGA technique and land use

Two types of uncertainties exist in an energy system optimisation mode: parametric and structural. The former type relates to imperfect knowledge of input values, and the latter type originates from the imperfect equations describing the system (DeCarolis et al., 2017). The modelling to generate alternatives (MGA) technique handles structural uncertainties. Other than attempting to perfect the model formulation, searching for alternatives in the near-optimal space might offer insights under structural uncertainties.

The MGA technique explores the near-optimal space and finds alternative systems that differ substantially from the optimal solution. The near optimal space is defined by a given slack value to increase the original objective value in a minimisation problem or to decrease the objective value in a maximisation problem. Several search directions for the alternatives have been proposed. The Hop-Skip-Jump method applied in DeCarolis (2011) and DeCarolis et al. (2016) minimises the weighted sum of decision variables appearing in the previous solutions. Another algorithm in the study by Price and Keppo (2017) looks for the furthest alternatives from the previous solutions. The third method, such as that used in the study by Neumann and Brown (2021), looks for plausible extrema – the maxima and minima values of the predefined groups.

Paper III in this thesis uses the MGA technique with search directions for minimum land impacts. Increasing opposition has been observed against certain renewable technologies due to the potential impact related to land or space. We modify the Balmorel model by applying the MGA technique to investigate the strategies that favour least land impact and the resulting costs of land saving.

New objective functions are defined to minimise land impact within the given additional system costs. First, an original Balmorel model is executed to determine the least cost level and the system configuration. A small percentage, referred to as the slack value, is then added to the system cost as an upper limit, while the new MGA objective functions are optimised. Figure 8 illustrates the methodology. Land impact is represented by the area requirement for the generation and storage installed capacities and fuel consumptions multiplied.

Initial Formulation

min.

$$C_{min} = \sum_{i \in I} c_i \cdot x_i$$

s.t.

$$x_i \in X$$

→

MGA Iteration $\forall\, \boldsymbol{m}, \boldsymbol{n}$

min

$$g_m(x_i) = \sum_{i \in I} land_{i,m} \cdot x_i$$

s.t.

$$x_i \in X$$

$$\sum_{i \in I} c_i \cdot x_i \le C_{min} \times (1 + slack_n)$$

Where

c	costs factors	$m \in M$	set of land impact functions
C_{min}	minimum system cost	$n \in N$	set of slack values
g	land impact functions	$slack$	slack values
$i \in I$	set of decision variables	x	decision variables
$land$	land impact factors	X	set of feasible alternatives

Figure 8. Illustration of the methodology applying the MGA technique to search for the alternatives with minimum land impact.

Paper III defines five MGA objective functions to reflect the subjectiveness of impacted area boundaries and of land value. For example, the objective in the MinLand scenario searches for the alternative that requires overall the least land in all modelling countries combined, while the objective in the LowImpact scenario finds the alternative with the lowest sum of the ratio of the required area to the potential land area, excluding unfeasible or crop or wood land, in each country. The methodology can be applied to investigate other non-techno-economic aspects, such as job creation and equality. Paper III, which includes detailed methodology and data descriptions, is the first study to apply the MGA technique to the Balmorel model.

3.2.3 Flow-based transmission modelling

To ensure efficient use of grids, there is a push towards a flow-based (FB) market coupling approach. In current Nordic power markets, the net transfer capacities (NTC) between the bidding zones are calculated by TSOs by forecasting the overall grid situations to ensure the grid operational security while maximising total social welfare. With increasing shares of VRE generation, uncertainties add challenges in forecasting grid situations and meeting both grid operational security and maximal social welfare. The idea of the FB approach is to model the real limitation of the grid, i.e. thermal limits and Kirchhoff's circuit law, more accurately to bridge the gap between market flows and physical power flows. As illustrated in Figure 9, the FB approach has more relaxed transmission capacity constraints than the NTC approach and enables better grid utilisation (NEMO Committee, 2020; Nordic Regional Security Coordinator (RSC), 2020).

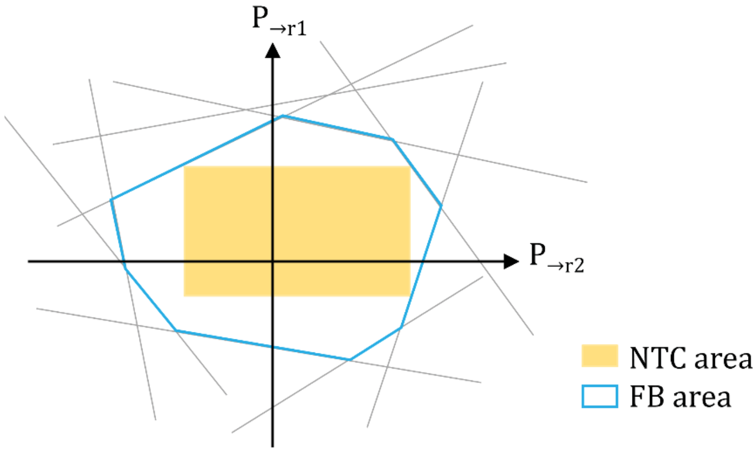

Figure 9. Illustration of the feasible areas in an AC grid of two power flows from one node to region r1 and to region r2 in the NTC approach (yellow) and the FB approach (blue). Black lines are the flow constraints from different transmission lines in the grid.

Energy system optimisation models, such as Balmorel, often have simplified power transmission modelling using the NTC approach. There are three levels of geographical resolution: country, region and area in Balmorel, where transmissions are defined as power exchanges between pairs of regions. For a good representation of the Northern European power markets, the Nordic countries consist of regions following the Nord Pool bidding zones, Germany consists of four regions and each of the other countries is one region. The amount of power exchange is constrained by the aggregated NTC for both AC and DC grids.

The FB approach for transmission modelling in Balmorel for AC grids is developed and applied in Paper IV. The maximum power exchange between regions is bounded by the actual thermal limit of the lines, and the flows are distributed following power transfer distribution factors (PTDFs) and net energy balances at each hour. Three AC subsystems – Scandinavia, Baltic and Central Europe – are clustered in the Balmorel model for current AC grids. DC grids and new transmission capacities still apply the NTC approach for simplification. Figure 10 illustrates the AC and DC transmission network setup in Balmorel, and further methodology and data descriptions can be found in the study by Gunkel et al. (2020) and in Paper IV.

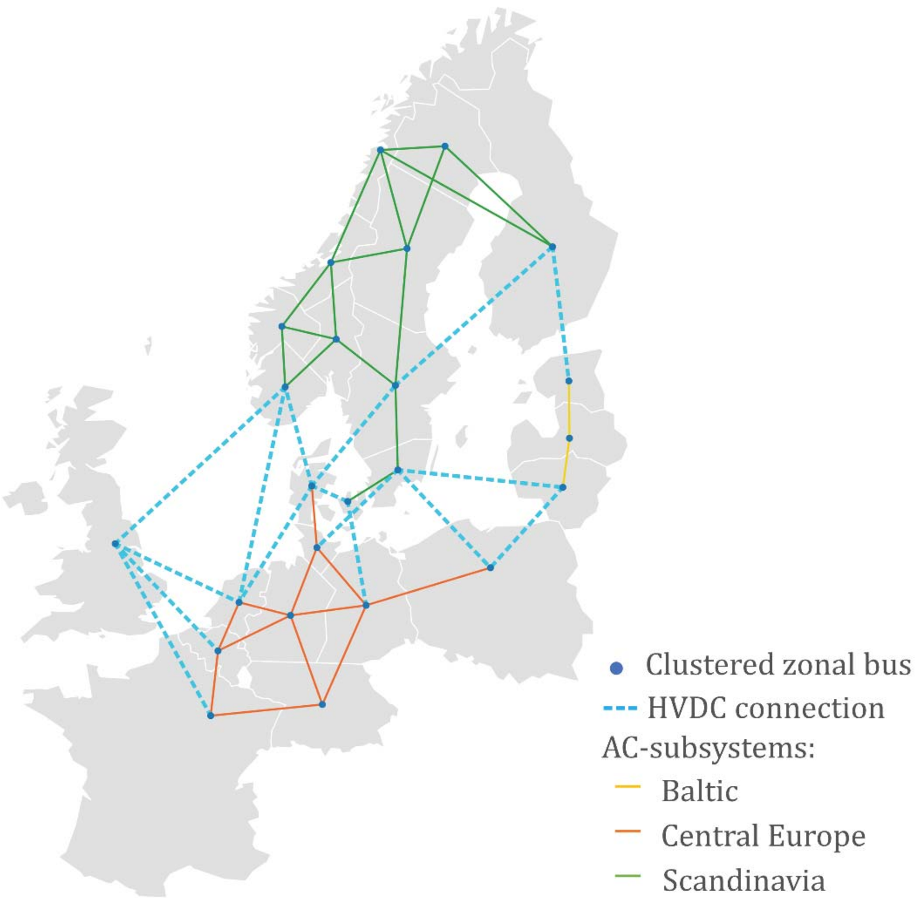

Figure 10. Transmission network setup the Balmorel model. The blue points correspond to the clustered zonal buses, the blue dash lines are high-voltage DC lines, the green, red and yellow lines are the lines within the 3 AC subsystems. Source: Gunkel et al. (2020).

4 Results

4.1 Decentralised heating decarbonisation boosts electricity demand and seasonality challenges

Paper II analyses the effect of full decarbonisation of heat by expanding the scope of the Balmorel model to cover decentralised heat as well as centralised power and heat production. Emission caps that comply with the EU's 2030 targets of both ETS and non-ETS sectors, followed by linear reduction to zero CO_2 emissions by 2050, are set. Paper II analyses five scenarios: three (HIGH, LOW and DH) varying in heating demand development, one (CLEANGAS) with emission-free gas and one (NOIDVH) without decentralised heating sector as a comparison. The current scale of the decentralised demand in the modelling country is estimated at around 2214 TWh, in addition to the 483 TWh of district heat demand. Towards 2050, electrification through heat pumps and hybrid systems is found to be an optimal and robust decarbonisation solution across the scenarios.

Overlooking decentralised heating, decarbonisation is likely leading to underestimation of future electricity demand. In the HIGH scenario, where no significant change in heating efficiency improvement or in district heating expansion is assumed, almost 700 TWh of electricity will be required for heating, three times higher than today's level. In the LOW scenario, assuming a 43% decrease in demand for space heating, there is still 465 TWh of electricity required for heating. In addition to the annual electricity demand, the peak load is much higher than without considering decentralised heating decarbonisation. The modelling results show Germany as the most impacted country, where the peak load in the HIGH scenario is 47% higher than that in the NOIDVH scenario.

The need for electricity stimulates more renewable installed capacities, especially for wind. In the NOIDVH scenario, four times today's wind capacity is installed by 2050, reaching 573 GW, and another 167 GW of wind will be required in the HIGH scenario. Even with the assumptions of building efficiency improvement or district heat expansion, an additional 41-63 GW of wind, compared to the NOIDVH scenario, will be installed in the DH or LOW scenarios. Such an amount of wind power installation might face strong opposition. Heating demand has strong seasonality, which is especially challenging in decentralised heating, where seasonal storage solutions are limited compared to centralised systems. Seasonal price differences become extreme, but the excess electricity generation in summer, if addressed well, offers opportunities for power-to-X applications and seasonal storage solutions.

4.2 Land required for energy grows four times in the least-cost solution, and seeking alternatives adds costs and risks

Paper III addresses the opposition originating from land conflicts by searching for the alternatives in the near optimal space of the least-cost solution given by the Balmorel model. It is assumed that the electricity demand increases by 48% in 2040 from today's level, and an emission cap is applied. The least-cost solution suggests that, in total, 1428 GW power generation capacity is installed by 2040, including 588 GW solar PV, 448 GW onshore wind, 67 GW nuclear and 44 GW offshore wind. With the assumed land factors, 1.2% land area will be used for energy production in 2040, four times today's level. The share of required land in the least-cost solution remains low compared to 26.2% of land eligible for onshore wind in Europe, as shown by the result in the land eligibility analysis by Ryberg et al. (2020).

When the optimisation objective alters to find the system with the least land requirement, nuclear energy and offshore wind play bigger roles, and fewer installed capacities are needed. Increasing the system costs by 1% reduces the land requirements by 16%, while a 10% increase in system costs reduces the land requirements by 60%. Dividing the cost increase by land avoidance shows that the cost of land avoidance ranges from €200 k/km^2 with a 1% increase in system costs to €550 k/km^2 with a 10% increase in system costs. The resulting costs are significantly high compared to the market prices of non-building land or the compensation to landowners for environmental reasons. Prioritising nuclear power and offshore wind over PV and onshore wind for the energy transition might ease land conflicts, but they are neither controversy-free solutions. Construction is more complex, investment costs are higher and there are safety and environmental concerns associated with these alternatives.

Countries take different approaches to limit land impact depending on their energy policies, nature resource conditions and the perceived importance of land preservation of various land types. Belgium, the Netherlands and Germany are the top three countries that have the highest shares (3-4%) of land for energy production with the least-cost solution. Latvia, Sweden and Norway have the lowest shares (0.1-0.2%). In the MinLand scenario, none of the countries use more than 2% of the land for energy production. The LowImpact scenario assumes that the countries prefer to occupy fewer shares of land use over agricultural and forest areas. This assumption of land type preference has limited impact on the UK, where some onshore wind and PV capacities remain. By contrast, many capacities in Nordics shift offshore in the Low Impact scenario. In the EcoSystem scenario, the UK shifts production offshore, but PV in the Continent and onshore wind in the Nordics retain their shares. Local assessments are needed for land conflict studies to give more tailored solutions, but Paper III illustrates the compromises in cost-effective energy transition and mitigating land conflicts.

4.3 Asymmetric benefits and costs of increased cross-border transmission

Paper IV analyses the effects of cross-border transmission on the power market and energy systems by comparing a scenario with endogenous transmission investments (optimal) to a scenario with only existing and planned projects (planned). A moderate growth in ETS quota price from 17 €/tCO_2 in 2020 to 54 €/tCO_2 in 2050 is assumed. The modelling results show that the optimal system will give an additional 76 GW cross-border transmission by 2050 on top of the 21 GW that is already planned between 2020 and 2030. Figure 11 shows a comparison of the given capacity assumptions and the optimal investment results. The largest expansions connect the Nordics and West-central Europe, such as between Denmark and the Netherlands, Norway and the UK, and a new line between Sweden and Poland. With the additional transmission capacities, total system costs are 5% lower, and CO_2 emissions are 40% less than in the planned scenario between 2030 and 2050.

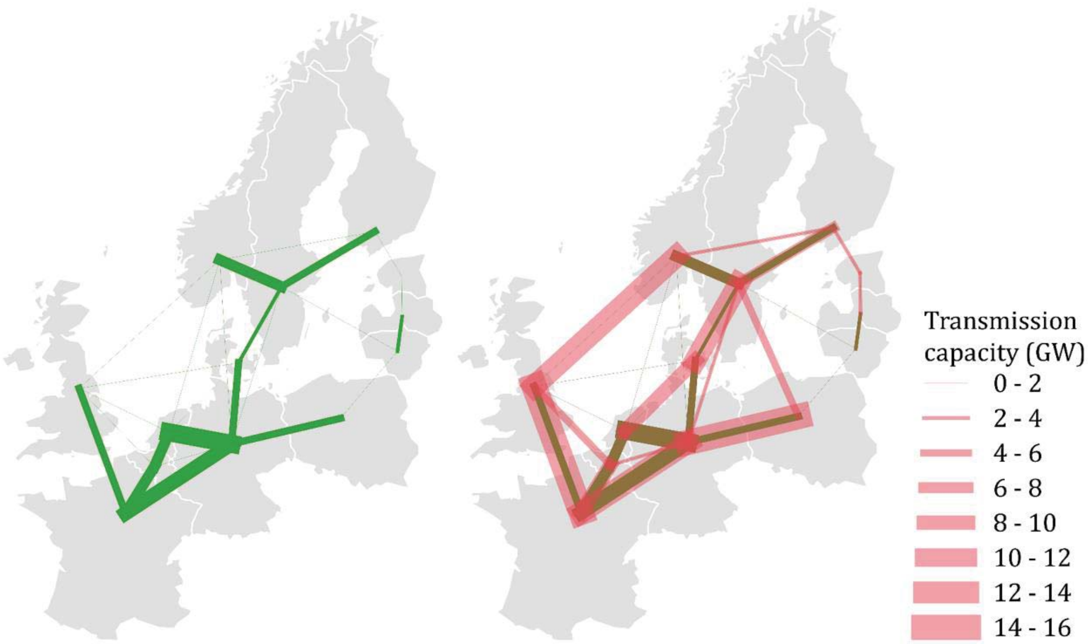

Figure 11. Cross-border transmission capacity in the planned scenario (left) and in the optimal scenario (right) in 2050.

While the systemwide benefits are clear, not all power market stakeholders gain equally from increased cross-border transmission. As explained in Section 2.3, producers benefit more in the low price areas, and consumers benefit more in the high price areas. For the analysis in Paper IV, the countries are aggregated to north and west regions. The north region, covering the Nordic and Baltic countries, has good hydro and wind resources, and the west region has larger electricity demand, better solar resources and some shares of power generation from fossil fuels. In the optimal scenario, 36% of the cross-border transmission capacities connect a country in the north to another in the west region. They enable better utilisation of renewable resources to substitute for coal- and gas-based generation. The generation portfolio shows that 30 GW of fossil fuel-based generation capacity in the west region is replaced by 39 GW of wind, two-thirds of which is installed in the north region. Wind power producers in the north region receive 67% higher revenues in the optimal scenario than in the planned scenario. Hydropower producers are another power market stakeholder that benefits the most from increased cross-border transmission. Even under the assumption of no capacity expansion, the flexible hydropower production receives 68% higher revenues in the optimal scenario than in the planned scenario. Increased transmission speeds up the energy transition and renewable integration. Gas power is less needed, and its producer revenues are 57% less in the optimal scenario.

Consumers experience the opposite. With more cross-border transmission, consumer costs of electricity in the north region are 21% higher, but those in the west region are 6% lower.

Paper IV shows that cross-border transmission bring overall benefits, especially to wind power deployment. No significant electrification is considered in Paper IV, and little change in demand is assumed. Paper II shows the importance of wind power in heating decarbonisation and the seasonality challenges. The benefits of cross-border transmission will be stronger with more electrification. Nevertheless, it is important to address the concerns of asymmetrically distributed benefits through, for example, international cooperation or policy design.

5 Discussion

5.1 Contributions and comparisons with existing literature

In light of the energy transition, this thesis contributes insights from thorough modelling analyses of the identified emerging challenges that have been relatively less discussed. The sub-objectives are defined after the Paper I review of Nordic power market outlooks, which reflect the respective perspectives of the key power market stakeholders. The direct expert survey by Sovacool et al. (2018) shows that the integration of renewables and the electrification of transport are the most frequently mentioned challenges in the Nordics' energy transition, and public opposition or political will are among the least mentioned challenges. The technical aspect of renewable integration is addressed by the reviewed outlooks with the use of advanced energy models, which nevertheless fall short of covering final energy products beyond electricity and district heat. The impact of electrification is thus limited to the assumptions of increasing electricity demand in some of the reviewed scenarios. Although the survey did not show significant social challenges, there are recent examples of social opposition hindering project realisation. The non-techno-economic aspects are translated to input assumptions and restrictions in the energy system analysis and affect output results. As Pfenninger et al. (2014) point out, addressing the human dimensions is among the new challenges for energy system models, but there is still room for improvement in this regard in the reviewed outlooks. Thus, Papers II to IV focus on the challenges related to electrification and human dimensions.

The importance of electrification of the non-power sector is receiving increasing attention towards deep decarbonisation. One of the key messages of the recent project Nordic Clean Energy Scenarios (Wråke et al., 2021) concludes that direct electrification is the centrepiece of carbon neutrality. The importance of expanding sectoral coverage of energy system analyses is twofold. On the one hand, sector coupling provides system flexibility that are beneficial to renewable integration. On the other hand, the total scales and hourly profiles of electricity demand will alter due to various end-use purposes. A recent survey by Chang et al. (2021) also shows the trend of increasing cross-sectoral coverage in energy system models, especially transport and district heating. Paper II covers the gap in international studies of decentralised heating, which takes a large share in final energy consumption but has yet to be decarbonised. The human dimension in Paper II is represented by introducing parameters to delay the technology switch to mimic the (un)willingness of the individual users to shift. The finding that heat pumps are the most cost-effective technology to supply decarbonised decentralised heating is in line with Knobloch et al. (2019), excluding solar heating. In terms of peak load, the report by Kavvadias et al. (2019) estimates winter peak will be 41% higher than today in full heating electrification, and according to Paper II it will be, on average, 21% higher than without modelling decentralised heat decarbonisation. Allowing endogenous investment, Paper II also reveals that the required renewable capacity, especially wind energy, might be significantly higher after considering decentralised heating decarbonisation.

Some climate-friendly technologies bring benefits in the techno-economic aspects of the energy transition but encounter challenges in the social-political dimensions, and in Northern Europe, wind turbines and transmission lines are such examples (Bolwig et al., 2020). With an endogenous investment methodology, the results in Papers II and III show the importance of wind energy in a cost-efficient low-carbon future, especially when the demand growth due to electrification is taken into account. In the study by Bolwig et al. (2020), the lack of social acceptance is translated as added investment costs to the targeted technology (onshore wind) before the optimisation looking for the most cost-efficient solution. In Paper III, the approach tackles land impact, which is the presumed reason for the lack of social acceptance. Cost efficiency is no longer the sole objective, and extra costs can be allocated to the investment options that cause less land impact. While the quantified results are sensitive to the assumptions of costs and land impact in both approaches, they reach the same conclusion that restricting onshore wind will likely shift the generation mix towards more solar PV, offshore wind or nuclear power (Paper III). The ranking of land use is not indisputable depending on the definition. For example, Dijkman and Benders (2010) find that in Northern Europe, the distance driven with electric vehicles powered by wind is more than double that powered by solar PV of the same land use. The alternative options are neither impact free. Radioactive waste disposal and safety have been major concerns of nuclear power. Whether the environmental and social impact of offshore wind installation is less than onshore is inconclusive because of limited knowledge of the offshore field, and impact assessments should be done on a case-by-case basis (Kaldellis et al., 2016).

Paper IV demonstrates the positive correlation between cross-border transmission and wind energy, in line with findings in Roques et al. (2010) and Neumann and Brown (2021). The optimal transmission capacity by 2050 for cost saving is four times today's level in the NTC approach in Paper IV, which is in line with the findings of the four times in Child et al. (2019), the nine times in Schlachtberger et al. (2017), and for the strongest balancing reduction, the 11.5 times in Rodríguez et al. (2014). The majority of the benefit can be achieved with less than half of the optimal capacity expansion (Rodríguez et al., 2014; Schlachtberger et al., 2017), and the important message is to identify the no-regret investment (Wråke et al., 2021). The transmission grid expansion is crucial to timely energy transition in bringing system-wide benefits, which is not mutually exclusive from other flexibility measures (Allard et al., 2020; Gea-Bermúdez et al., 2021; Thellufsen & Lund, 2017). While the benefits of cross-border transmission are well understood, Paper IV also quantifies the concerns for welfare distribution in the power market, which is not mentioned in the above mentioned literature. Understanding the concerns is the first step, and international cooperation and adequacy policy and market designs are required to overcome the challenges.

5.2 Limitations and future research

The three modelling studies include some of the emerging challenges in the European energy transition. Uncertainty has been one of the main concerns for energy transition research, and the studies in this thesis address uncertainties using deterministic scenarios and the MGA technique. One weakness is the lack of advanced assessment of parametric uncertainties, especially considering the wide ranges of future fuel and emission quota price assumptions in the reviewed scenarios and their high dependency on power prices shown in Paper I, as illustrated in Figure 12. Future research can address parametric uncertainties through global sensitive analysis and Monte Carlo analysis (DeCarolis et al., 2017; Yue et al., 2018). A Finish case study by Pilpola and Lund (2020) using Monte Carlo analysis highlights that the optimal system based on single deterministic assumptions may become unreliable under variation in the model inputs.

Weather stochasticity is omitted in the three deterministic modelling studies, and on top of it, climate change adds uncertainties on both supply and demand sides. A case study by Seljom and Tomasgard (2015) with stochastic modelling of wind power generation shows lower wind power investments than using a deterministic approach. Golombek et al. (2022) soft-link an equilibrium and a stochastic European energy model, to take into account the impact of the uncertain load and VRE generation on investments, and the results show that a pure deterministic approach underestimates the need for transmission and battery capacity. Future energy transition research should ensure that the proposed strategies are robust to weather and climate uncertainties and assess the associated risks.

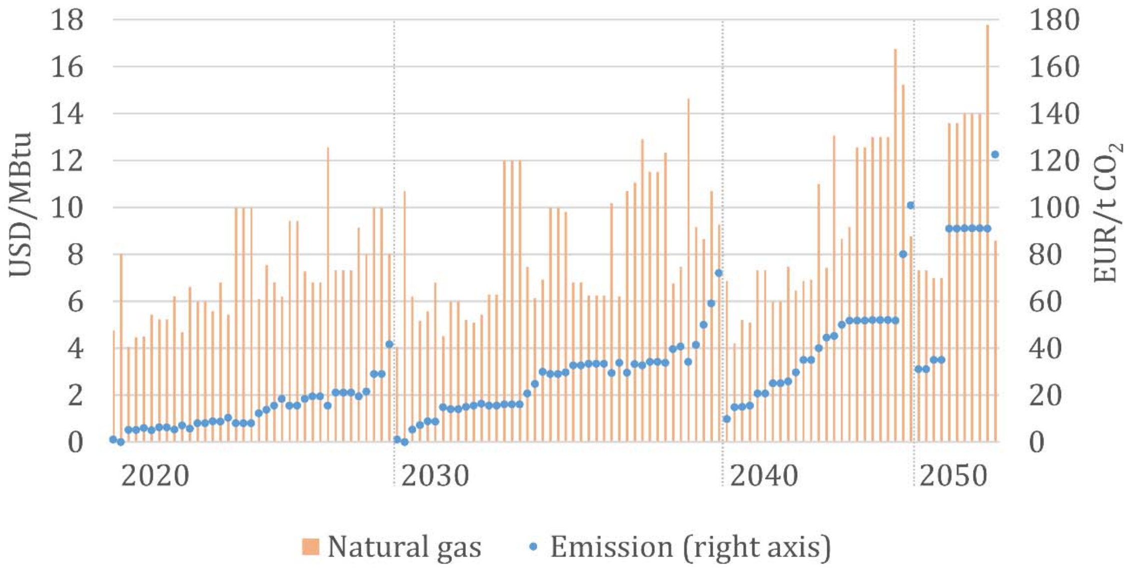

Figure 12. Illustration of the gas and emission price assumptions of the reviewed scenarios in Paper I. Each column represents one reviewed scenario.

On the demand side, besides decentralised heating, deep decarbonisation of transport and industry sectors will also impact the electricity system through electrification and sector coupling. These end-use demands are not fully represented in Paper II, although smart charging of private electric vehicles and simplified demand response are included as flexibility options. An analysis covering all end-use sectors provides more comprehensive insights into challenges in further decarbonisation. Based on the seasonality challenge shown in Paper II, future energy transition research can also investigate which strategies mitigate peak demand, such as building retrofitting (Zeyen et al., 2021), or which offer seasonal storage solutions, such as hydrogen (Petkov & Gabrielli, 2020).

On the supply side, future research can identify alternative system configurations minimising other types of impact, such as inequality or use of materials (Sasse & Trutnevyte, 2020), using a similar method as in Paper III. One improvement of this methodology is to take heterogenous values and renewable resources into account. For example, applying assumptions based on local surveys and using GIS tools can deliver a more tailored analysis. Papers III and IV show the benefits and compromises deviating from the cost-optimal systems. The next step is to deliver them to the public with full transparency and identify the no-regret options, such as through iterations of modelling studies and public consultations. Nevertheless, it is still important to maintain larger geographic coverage to avoid overlooking the spillover effect.

6 Conclusions

This thesis has investigated three emerging challenges for achieving speedier and broader decarbonisation of the Northern European energy system. Electrification with electricity from renewables is one major mitigation strategy for the non-power sectors. This mitigation strategy will affect the power demand profile and increase the scale of electricity demand. Meeting the new demand levels will require more renewable energy deployment. Despite the declining technology costs, increasing challenges from non-techno-economic perspectives have been observed. One social concern against renewable technologies has risen from their low installed power densities, leading to increasing land impact and land-use conflicts. There have been doubts against international cooperation via power transmission. Despite the overall increase in system efficiency and flexibility, benefits are distributed asymmetrically among countries, and electricity costs increase for consumers in low price areas. The review in Paper I reveals that these challenges have not been thoroughly addressed in the Nordic power market outlooks published between 2016 and 2018. Thus, this thesis includes three modelling studies to respectively analyse the effect of non-power sector decarbonisation (focusing on decentralised heat), the options to minimise land use conflicts and the trade-offs of cross-border power transmission.

The modelling results in Paper II show that electrification through heat pumps and hybrid systems supplies the most cost-efficient decarbonised heat. The amount of additional electricity demand varies depending on the assumptions of building efficiency improvement and district heating development, but all the scenarios show that decentralised heating decarbonisation affects future electricity demand and the need for renewables, particularly wind power. In the HIGH scenario, almost 700 TWh extra electricity will be needed for heating decarbonisation, and 740 GW wind plus 189 GW solar should be installed in the modelling countries. Future electricity demand will likely inherit the strong seasonality from heating demand, causing higher winter peak loads, potentially excess electricity in summer and significant seasonal power price differences. Countries such as Germany and the UK, where a large amount of heat is currently supplied by fossil fuels, are the most impacted.

The results in Paper III suggest that onshore wind and solar PV take the largest shares in the electricity mix under the least-cost solution. Although the rising renewable deployment will require larger land and space than the current system, the overall percentage of land use for energy facilities remains at 1.2% in the modelling scope. Potential land conflicts can be mitigated by shifting towards costlier systems with higher shares of offshore wind and nuclear power. Nonetheless, neither offshore wind nor nuclear power are controversy-free options, with higher risks in costs and safety than onshore wind and solar PV. The implied costs per land avoided are considerably high compared to the compensation for ecosystem conservation reasons or to the land market prices.

Paper IV demonstrates that allowing for transmission investments to increase cross-border interconnection can contribute to lower costs and emissions in future energy systems. The model invests 76 GW cross-border transmission capacities on top of the existing and planned capacities between 2030 and 2050. Through power transmission, resources can be utilised more efficiently. The cooperation is particularly beneficial to wind power development in the Nordics, where good wind resources can be sent south to substitute fossil-based generations. Regional power price differences decrease, which causes the opposite impact to producers and consumers. Hydropower and wind producers in the Nordics receive 67% growth in revenues, while consumers will have to pay 21% higher prices. Although power prices in the Nordics increase, they remain relatively low in an international context. The asymmetric distributed benefits indicate the need for interconnection and proper policy designs to overcome the barriers and utilise the system-level benefits of cross-border power transmission.

A main conclusion in this thesis is that there is a significant need for electricity from renewables, but the challenges faced by the relevant technologies are shifting from techno-economic towards non-techno-economic aspects. Research-based analysis provides the basis for rational discussions. For a successful and timely energy transition, clear communication of trade-offs and compromises of various choices will be crucial.

7 References

Allard, S., Mima, S., Debusschere, V., Quoc, T. T., Criqui, P. & Hadjsaid, N. (2020). European transmission grid expansion as a flexibility option in a scenario of large scale variable renewable energies integration. *Energy Economics*, 87: 104733. DOI: 10.1016/j.eneco.2020.104733.

Amundsen, B. (2021). Neppe særlig mer vindkraft de neste 5 til 10 årene. *forskning.no*, 20.08.2021. Available at: https://forskning.no/energi-politikk/neppe-saerlig-mer-vindkraft-de-neste-5-til-10-arene/1899711 (accessed: 02.09.2021).

Becker, S., Rodriguez, R. A., Andresen, G. B., Schramm, S. & Greiner, M. (2014). Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. *Energy*, 64: 404-418. DOI: 10.1016/j.energy.2013.10.010.

Bird, L., Lew, D., Milligan, M., Carlini, E. M., Estanqueiro, A., Flynn, D., Gomez-Lazaro, E., Holttinen, H., Menemenlis, N., Orths, A., et al. (2016). Wind and solar energy curtailment: a review of international experience. *Renewable & Sustainable Energy Reviews*, 65: 577-586. DOI: 10.1016/j.rser.2016.06.082.

Bolwig, S., Bolkesjø, T. F., Klitkou, A., Lund, P. D., Bergaentzlé, C., Borch, K., Olsen, O. J., Kirkerud, J. G., Chen, Y.-k., Gunkel, P. A., et al. (2020). Climate-friendly but socially rejected energy-transition pathways: the integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. *Energy Research & Social Science*, 67: 101559. DOI: 10.1016/j.erss.2020.101559.

Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy*, 160: 720-739. DOI: 10.1016/j.energy.2018.06.222.

Brunge, K., Alterbeck, J., Böhlmark, E., Helander, E., Hellström, E., Nilsberth, A., & Keijser, M. R. (2019). Långsiktig marknadsanalys. Available at: https://www.svk.se/siteassets/om-oss/rapporter/2018/langsiktig-marknadsanalys-2018.pdf (accessed: 01.11.2021).

Bøhnsdalen, E. T., Døskeland, I. H., Västermark, K. L., Holmefjord, V., Christiansen, L., & Gunnerød, J. L. (2018). Langsiktig markedsanalyse, Norden og Europa 2018–2040. Available at: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/langsiktig-markedsanalyse-norden-og-europa-2018-40.pdf (accessed: 24.03.2020).

Cao, K.-K., Pregger, T., Haas, J. & Lens, H. (2021). To prevent or promote grid expansion? Analyzing the future role of power transmission in the European energy system. *Frontiers in Energy Research*, 8 (371). DOI: 10.3389/fenrg.2020.541495.

Capion, K., Stryg, M., & Poulsen, K. R. (2018). Elpris Outlook 2018. Available at: https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2018-03/Elpris_Outlook_2018_0.pdf (accessed: 01.11.2021).

Chang, M., Thellufsen, J. Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H. & Østergaard, P. A. (2021). Trends in tools and approaches for modelling the energy transition. *Applied Energy*, 290: 116731. DOI: 10.1016/j.apenergy.2021.116731.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. *Energy Research & Social Science*, 37: 175-190. DOI: 10.1016/j.erss.2017.09.015.

Child, M., Kemfert, C., Bogdanov, D. & Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy*, 139: 80-101. DOI: 10.1016/j.renene.2019.02.077.

DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., Pye, S., Strachan, N., Trutnevyte, E., Usher, W., et al. (2017). Formalizing best practice for energy system optimization modelling. *Applied Energy*, 194: 184-198. DOI: 10.1016/j.apenergy.2017.03.001.

DeCarolis, J. F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics*, 33 (2): 145-152. DOI: 10.1016/j.eneco.2010.05.002.

DeCarolis, J. F., Babaee, S., Li, B. & Kanungo, S. (2016). Modelling to generate alternatives with an energy system optimization model. *Environmental Modelling & Software*, 79: 300-310. DOI: 10.1016/j.envsoft.2015.11.019.

Després, J., Hadjsaid, N., Criqui, P. & Noirot, I. (2015). Modelling the impacts of variable renewable sources on the power sector: reconsidering the typology of energy modelling tools. *Energy*, 80: 486-495. DOI: 10.1016/j.energy.2014.12.005.

Dijkman, T. J. & Benders, R. M. J. (2010). Comparison of renewable fuels based on their land use using energy densities. *Renewable and Sustainable Energy Reviews*, 14 (9): 3148-3155. DOI: 10.1016/j.rser.2010.07.029.

Directorate-General for Energy. (2019). *Electricity interconnections with neighbouring countries*. European Commission.

Dugstad, A., Grimsrud, K., Kipperberg, G., Lindhjem, H. & Navrud, S. (2020). Acceptance of wind power development and exposure – not-in-anybody's-backyard. *Energy Policy*, 147: 111780. DOI: 10.1016/j.enpol.2020.111780.

Energimyndigheten. (2019). Scenarier över Sveriges energisystem 2018. Available at: http://www.profu.se/pdf/ER_2019_07webb.pdf (accessed: 01.11.2021).

Energinet. (2017). Energinets analyseforudsætninger. Available at: https://energinet.dk/Analyse-og-Forskning/Analyseforudsaetninger/Analyseforudsaetninger-2017 (accessed: 01.11.2021).

Enevoldsen, P., Permien, F.-H., Bakhtaoui, I., Krauland, A.-K. v., Jacobson, M. Z., Xydis, G., Sovacool, B. K., Valentine, S. V., Luecht, D. & Oxley, G. (2019). How much wind power potential does Europe have? Examining European wind power potential with an enhanced socio-technical atlas. *Energy Policy*, 132: 1092-1100. DOI: 10.1016/j.enpol.2019.06.064.

Enevoldsen, P. & Jacobson, M. Z. (2021). Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. *Energy for Sustainable Development*, 60: 40-51. DOI: 10.1016/j.esd.2020.11.004.

European Commission. (2015). *Communication from the commission to the european parliament and the council: achieving the 10% electricity interconnection target – making Europe's electricity grid fit for 2020*, COM(2015)82. Brussels: European Commission.

European Commission. (2017). *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions – communication on strengthening Europe's energy networks*, COM(2017)718. Brussels: European Commission.

European Commission. (2018). *In-depth analysis in support on the COM(2018)773: a clean planet for all – a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Brussels: European Commission.

European Commission. (2019a). *Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions – the European Green Deal, COM(2019)640*. Brussels: European Commission.

European Commission. (2019b). *Preparing the ground for raising long-term ambition – EU climate action progress report 2019*, COM(2019)559. Brussels: European Commission.

European Union. (2018). *Regulation (EU) 2018/842 of the European parliament and of the council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013*.

Eurostat. *Energy consumption in households*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households (accessed: 02.09.2021).

EWEA. (2003). *A summary of opinion surveys on wind power*. European Wind Energy Association.

Foxon, T. J. (2011). A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecological Economics*, 70 (12): 2258-2267. DOI: 10.1016/j.ecolecon.2011.07.014.

Gea-Bermúdez, J., Jensen, I. G., Münster, M., Koivisto, M., Kirkerud, J. G., Chen, Y.-k. & Ravn, H. (2021). The role of sector coupling in the green transition: a least-cost energy system development in Northern-central Europe towards 2050. *Applied Energy*, 289: 116685. DOI: 10.1016/j.apenergy.2021.116685.

Gogia, R., Endresen, H., Haukeli, I. E., Hole, J., Birkelund, H., Aulie, F. H., Ann Østenby, Magnus Buvik, Bergesen, B. (2019). Langsiktig kraftmarkedsanalyse 2019-2040. Available at: http://publikasjoner.nve.no/rapport/2019/rapport2019_41.pdf (accessed: 01.11.2021).

Golombek, R., Lind, A., Ringkjøb, H.-K. & Seljom, P. (2022). The role of transmission and energy storage in European decarbonization towards 2050. *Energy*, 239: 122159. DOI: 10.1016/j.energy.2021.122159.

Gunkel, P. A., Koduvere, H., Kirkerud, J. G., Fausto, F. J. & Ravn, H. (2020). Modelling transmission systems in energy system analysis: A comparative study. *Journal of Environmental Management*, 262: 110289. DOI: 10.1016/j.jenvman.2020.110289.

Helgeson, B. & Peter, J. (2020). The role of electricity in decarbonizing European road transport – development and assessment of an integrated multi-sectoral model. *Applied Energy*, 262: 114365. DOI: 10.1016/j.apenergy.2019.114365.

Holttinen, H. (2005). Hourly wind power variations in the Nordic countries. *Wind Energy*, 8 (2): 173-195. DOI: 10.1002/we.144.

Huber, M., Dimkova, D. & Hamacher, T. (2014). Integration of wind and solar power in Europe: assessment of flexibility requirements. *ENERGY*, 69: 236-246. DOI: 10.1016/j.energy.2014.02.109.

IEA. (2021). *Data and statistics – Data browser*. Available at: https://www.iea.org/data-and-statistics/data-browser?country=EU28?country=EU28 (accessed: 27.08.2021).

Impram, S., Nese, S. V. & Oral, B. (2020). Challenges of renewable energy penetration on power system flexibility: a survey. *ENERGY STRATEGY REVIEWS*, 31. DOI: 10.1016/j.esr.2020.100539.

Ioannidis, R. & Koutsoyiannis, D. (2020). A review of land use, visibility and public perception of renewable energy in the context of landscape impact. *Applied Energy*, 276: 115367. DOI: 10.1016/j.apenergy.2020.115367.

IRENA. (2016). *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Power_to_Change_2016.pdf (accessed: 01.11.2021).

IRENA. (2017). *Electricity Storage and Renewables: Costs and Markets to 2030*. Abu Dhabi: International Renewable Energy Agency.

IRENA. (2021). *Renewable Power Generation Costs in 2020*. Abu Dhabi: International Renewable Energy Agency.

Jensen, I. G., Wiese, F., Bramstoft, R. & Münster, M. (2020). Potential role of renewable gas in the transition of electricity and district heating systems. *Energy Strategy Reviews*, 27: 100446. DOI: 10.1016/j.esr.2019.100446.

Kaldellis, J. K., Apostolou, D., Kapsali, M. & Kondili, E. (2016). Environmental and social footprint of offshore wind energy: comparison with onshore counterpart. *Renewable Energy*, 92: 543-556. DOI: 10.1016/j.renene.2016.02.018.

Kannan, R. (2018). Dynamics of long-term electricity demand profile: insights from the analysis of Swiss energy systems. *Energy Strategy Reviews*, 22: 410-425. DOI: 10.1016/j.esr.2018.10.010.

Kavvadias, K., Jiménez-Navarro, J. P. & Thomassen, G. (2019). *Decarbonising the EU heating sector – integration of the power and heating sector*. EUR 29772 EN. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-08386-3; JRC114758.

Knobloch, F., Pollitt, H., Chewpreecha, U., Daioglou, V. & Mercure, J.-F. (2019). Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C. *Energy Efficiency*, 12 (2): 521-550. DOI: 10.1007/s12053-018-9710-0.

Li, P.-H., Keppo, I. & Strachan, N. (2018). Incorporating homeowners' preferences of heating technologies in the UK TIMES model. *Energy*, 148: 716-727. DOI: 10.1016/j.energy.2018.01.150.

Livgard, E. F. (2020). *Klimabarometer 2020*. Kantar. Available at: https://www.forskningsradet.no/contentassets/b8513ab2d46f47769707649e4c941f9e/klimabarometer-2020-kantar.pdf (accessed: 02.09.2021).

Lygnerud, K. (2018). Challenges for business change in district heating. *Energy, Sustainability and Society*, 8 (1): 20. DOI: 10.1186/s13705-018-0161-4.

Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy*, 3 (8): 628-633. DOI: 10.1038/s41560-018-0171-7.

Millot, A. & Maïzi, N. (2021). From open-loop energy revolutions to closed-loop transition: what drives carbon neutrality? *Technological Forecasting and Social Change*, 172: 121003. DOI: 10.1016/j.techfore.2021.121003.

Mytilinou, V., Kolios, A. J. & Di Lorenzo, G. (2017). A comparative multi-disciplinary policy review in wind energy developments in Europe. *International Journal of Sustainable Energy*, 36 (8): 754-774. DOI: 10.1080/14786451.2015.1100194.

NEMO Committee. (2020). *EUPHEMIA Public Description - Single Price Coupling Algorithm*. Nominated Electricity Market Operators (NEMOs). Available at: https://www.nordpoolgroup.com/4adb91/globalassets/download-center/single-day-ahead-coupling/euphemia-public-description.pdf (accessed: 01.11.2021).

Neumann, F. & Brown, T. (2021). The near-optimal feasible space of a renewable power system model. *Electric Power Systems Research*, 190: 106690. DOI: 10.1016/j.epsr.2020.106690.

Nordic Energy Research. *Flex4RES: Flexibility for Variable Renewable Energy Integration in the Nordic Energy Systems*. Available at: https://www.nordicenergy.org/flagship/flex4res/ (accessed: 20.07.2020).

Nordic Regional Security Coordinator (RSC). (2020). *Capacity Calculation Methodology*. Available at: https://nordic-rsc.net/flow-based/ (accessed: 02.09.2021).

Osorio, S., Pietzcker, R. & Tietjen, O. (2020). *Documentation of LIMES-EU - A long-term electricity system model for Europe*. Potsdam Institute for Climate Impact Research.

Palmer-Wilson, K., Donald, J., Robertson, B., Lyseng, B., Keller, V., Fowler, M., Wade, C., Scholtysik, S., Wild, P. & Rowe, A. (2019). Impact of land requirements on electricity system decarbonisation pathways. *Energy Policy*, 129: 193-205. DOI: 10.1016/j.enpol.2019.01.071.

Papadis, E. & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. *Energy*, 205: 118025. DOI: 10.1016/j.energy.2020.118025.

Petkov, I. & Gabrielli, P. (2020). Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. *Applied Energy*, 274: 115197. DOI: 10.1016/j.apenergy.2020.115197.

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

Pilpola, S. & Lund, P. D. (2020). Analyzing the effects of uncertainties on the modelling of low-carbon energy system pathways. *Energy*, 201: 117652. DOI: 10.1016/j.energy.2020.117652.

Poulsen, K. R., Stryg, M., & Capion, K. (2019). Elpris outlook 2019. Available at: https://www.danskenergi.dk/udgivelser/elpris-outlook-2019 (accessed: 01.11.2021).

Price, J. & Keppo, I. (2017). Modelling to generate alternatives: A technique to explore uncertainty in energy-environment-economy models. *Applied Energy*, 195: 356-369. DOI: 10.1016/j.apenergy.2017.03.065.

Ringkjøb, H.-K., Haugan, P. M. & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews*, 96: 440-459. DOI: 10.1016/j.rser.2018.08.002.

Rodríguez, R. A., Becker, S., Andresen, G. B., Heide, D. & Greiner, M. (2014). Transmission needs across a fully renewable European power system. *Renewable Energy*, 63: 467-476. DOI: 10.1016/j.renene.2013.10.005.

Roques, F., Hiroux, C. & Saguan, M. (2010). Optimal wind power deployment in Europe – a portfolio approach. *Energy Policy*, 38 (7): 3245-3256. DOI: 10.1016/j.enpol.2009.07.048.

Rosenbloom, D. (2017). Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change*, 43: 37-50. DOI: 10.1016/j.gloenvcha.2016.12.011.

Rotmans, J., Kemp, R. & van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight*, 3 (1): 15-31. DOI: 10.1108/14636680110803003.

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., et al. (2019). ENSPRESO – an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, 26: 100379. DOI: 10.1016/j.esr.2019.100379.

Ryberg, D. S., Caglayan, D. G., Schmitt, S., Linßen, J., Stolten, D. & Robinius, M. (2019). The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs. *Energy*, 182: 1222-1238. DOI: 10.1016/j.energy.2019.06.052.

Ryberg, D. S., Tulemat, Z., Stolten, D. & Robinius, M. (2020). Uniformly constrained land eligibility for onshore European wind power. *Renewable Energy*, 146: 921-931. DOI: 10.1016/j.renene.2019.06.127.

Sasse, J.-P. & Trutnevyte, E. (2020). Regional impacts of electricity system transition in Central Europe until 2035. *Nature Communications*, 11 (1): 4972. DOI: 10.1038/s41467-020-18812-y.

Schlachtberger, D. P., Brown, T., Schramm, S. & Greiner, M. (2017). The benefits of cooperation in a highly renewable European electricity network. *Energy*, 134: 469-481. DOI: 10.1016/j.energy.2017.06.004.

Seljom, P. & Tomasgard, A. (2015). Short-term uncertainty in long-term energy system models — A case study of wind power in Denmark. *Energy Economics*, 49: 157-167. DOI: 10.1016/j.eneco.2015.02.004.

Sovacool, B. K., Kester, J., de Rubens, G. Z. & Noel, L. (2018). Expert perceptions of low-carbon transitions: investigating the challenges of electricity decarbonisation in the Nordic region. *Energy*, 148: 1162-1172. DOI: 10.1016/j.energy.2018.01.151.

Suškevičs, M., Eiter, S., Martinat, S., Stober, D., Vollmer, E., de Boer, C. L. & Buchecker, M. (2019). Regional variation in public acceptance of wind energy development in Europe: what are the roles of planning procedures and participation? *Land Use Policy*, 81: 311-323. DOI: 10.1016/j.landusepol.2018.10.032.

The Balmorel Open Source Project. (2021). *Balmorel Energy System Model*. Available at: http://www.balmorel.com/index.php (accessed: 05.10.2021).

Thellufsen, J. Z. & Lund, H. (2017). Cross-border versus cross-sector interconnectivity in renewable energy systems. *Energy*, 124: 492-501. DOI: 10.1016/j.energy.2017.02.112.

Van Nuffel, L., Gorenstein Dedecca, J., Smit, T. & Rademaerers, K. (2018). *Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?* Policy Department for Economic, S. a. Q. o. L. P. & Policies, D.-G. f. I.

Warren, C. R., Lumsden, C., O'Dowd, S. & Birnie, R. V. (2005). 'Green On Green': Public perceptions of wind power in Scotland and Ireland. *Journal of Environmental Planning and Management*, 48 (6): 853-875. DOI: 10.1080/09640560500294376.

Wiese, F., Bramstoft, R., Koduvere, H., Pizarro Alonso, A., Balyk, O., Kirkerud, J. G., Tveten, Å. G., Bolkesjø, T. F., Münster, M. & Ravn, H. (2018). Balmorel open source energy system model. *Energy Strategy Reviews*, 20 (C): 26-34. DOI: 10.1016/j.esr.2018.01.003.

Wråke, M., Karlsson, K., Kofoed-Wiuff, A., Bolkesjø, T. F., Lindroos, T. J., Hagberg, M., Simonsen, M. B., Unger, T., Tennbakk, B., Jåstad, E. O., et al. (2021). *Nordic Clean Energy Scenarios – solutions for carbon neutrality*. Nordic Energy Research.

Yue, X., Pye, S., DeCarolis, J., Li, F. G. N., Rogan, F. & Gallachóir, B. Ó. (2018). A review of approaches to uncertainty assessment in energy system optimization models. *Energy Strategy Reviews*, 21: 204-217. DOI: 10.1016/j.esr.2018.06.003.

Zeyen, E., Hagenmeyer, V. & Brown, T. (2021). Mitigating heat demand peaks in buildings in a highly renewable European energy system. *Energy*, 231: 120784. DOI: 10.1016/j.energy.2021.120784.

Østergaard, P. A., Andersen, F. M. & Kwon, P. S. (2015). Energy systems scenario modelling and long term forecasting of hourly electricity demand. *International Journal of Sustainable Energy Planning and Management*, 7: 95-112. DOI: 10.5278/ijsepm.2015.7.8.

Paper I Chen, Y.-k., Hexeberg, A., Rosendahl, K.E. & Bolkesjø, T.F. 2021. Long-term trends of Nordic power market: A review. – WIREs Energy and Environment 10(6):e413. 23 pp. DOI: 10.1002/wene.413
Paper II Chen, Y.-k., Jensen, I.G., Kirkerud, J.G. & Bolkesjø, T.F. 2021. Impact of fossil-free decentralized heating on Northern European renewable energy deployment and the power system. – Energy 219: 119576. 14 pp. DOI: 10.1016/j.energy.2020.119576
Paper III Chen, Y.-k., Kirkerud, J.G. & Bolkesjø, T.F. Balancing GHG mitigation and land conflicts: Alternative Northern European energy system scenarios. – Applied Energy. (Submitted)
Paper IV Chen, Y.-k., Koduvere, H., Gunkel, P.A., Kirkerud, J.G., Skytte, K., Ravn, H. & Bolkesjø, T.F. 2020. The role of cross-border power transmission in a renewable-rich power system – A model analysis for Northwestern Europe. – Journal of Environmental Management 261:110194. 8 pp. DOI: 10.1016/j.jenvman.2020.110194

ISBN: 978-82-575-1899-8
ISSN: 1894-6402

NMBU
Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no

112874 / ANDVORDGRAFISK.NO