Department of Mathematics and Systems Analysis

# Optimization Models for Assessing Energy Systems in Transition

**Vilma Virasjoki**

Aalto University

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# Optimization Models for Assessing Energy Systems in Transition

**Vilma Virasjoki**

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# Abstract

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## Abstract

Energy systems are undergoing a major transition toward environmental sustainability. For instance, the European Union has implemented energy and climate policy targets for years 2020 and 2030 in order to reduce greenhouse gas emissions, increase renewable energy production and improve energy efficiency. However, because variable renewable energy sources (VRES) such as wind and solar power are intermittent, more flexibility is required from the energy system.

This dissertation analyzes the present energy transition through two lenses. First, it formulates mathematical models which are solved through optimization and complementarity techniques to determine optimal investment and operational decisions, in recognition of the stakeholders' different and even conflicting objectives. Second, these models provide insights into the Western European power market and Nordic energy systems by helping in the assessment of the technical, welfare, and emissions impacts of large-scale energy storage. Much emphasis is placed on the analysis of market efficiency, because large producers, in particular, may be able to affect markets in their favor. This kind of market power is studied especially in connection with investments into and operation of energy storage as well as the production of combined heat and power (CHP). Finally, the modeling of power transmission networks gives information about the combined effects of interconnected markets and the increasing share of VRES.

The models in this dissertation support energy policy-making in the present situation in which it is crucial to understand how the security of supply can be maintained without compromising sustainability and market efficiency. Overall, the models yield results which could hardly be obtained through empirical research, as the outcomes of ongoing developments and planned policies depend on the actions of all stakeholders.

**Keywords** energy systems modeling, optimization, energy storage, market power

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**Tiivistelmä**

Energiajärjestelmät ovat vahvassa murroksessa kohti ympäristön kannalta kestävämpää toimintaa. Esimerkiksi Euroopan Unionin energia- ja ilmastopolitiikan tavoitteina vuosille 2020 ja 2030 on vähentää kasvihuonekaasupäästöjä sekä lisätä uusiutuvan energian tuotantoa ja energiatehokkuutta. Uusiutuvan energian tuotanto kuitenkin vaihtelee, sillä tuuli- ja aurinkovoiman tuotanto riippuu sääolosuhteista. Meneillään oleva murros edellyttää näin yhä enemmän joustavuutta koko energiajärjestelmältä.

Tämä väitöskirja tarkastelee energiajärjestelmän muutosta kahdesta toisiaan täydentävästä näkökulmasta. Yhtäältä siinä rakennetaan matemaattisia malleja, joista voidaan määrittää optimaaliset investointi- ja operatiiviset päätökset optimoinnin ja komplementaarisen mallinuksen avulla ottamalla huomioon myös sidosryhmien erilaiset ja jopa ristiriitaisetkin tavoitteet. Toisaalta mallit tarjoavat tietoa Länsi-Euroopan sähkömarkkinasta sekä pohjoismaisesta energiajärjestelmästä tukemalla energian varastoinnin teknisten, taloudellisten, sekä päästövaikutusten arviointia. Markkinoiden tehokkuutta tarkastellaan erityisesti, koska varsinkin suuret tuottajat saattavat vaikuttaa markkinoihin omaksi edukseen. Tätä markkinavoimaa analysoidaan niin sähkön varastoinnin, varastoinvestointien kuin yhdistetyn sähkön- ja lämmöntuotannon (CHP) näkökulmista. Myös sähkönsiirtoa mallinnetaan eri maiden välisten siirtoyhteyksien ja kasvavan uusiutuvan energiantuotannon yhteisvaikutuksen arvioimiseksi.

Väitöskirjan mallit tukevat energia-alan ja -politiikan päätöksentekoa nykytilanteessa, jossa on ratkaisevan tärkeää ymmärtää, miten energian toimitusvarmuus voidaan taata kestävän kehityksen tai taloudellisen tehokkuuden tavoitteita vaarantamatta. Mallit antavat tuloksia, joita ei empiirisellä tutkimuksella juurikaan pystyttäisi tuottamaan, sillä nykykehityksen ja suunniteltujen poliittisten päätösten seuraamukset riippuvat kaikkien sidosryhmien toiminnasta.

**Avainsanat** energiajärjestelmien mallinnus, optimointi, energian varastointi, markkinavoima

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# List of Publications

This doctoral dissertation consists of a summary article and of the following publications, which are referred to in the text by their numerals.

**I.** Virasjoki, V., Rocha, P., Siddiqui, A. S., and Salo, A. 2016. Market impacts of energy storage in a transmission-constrained power system. *IEEE Transactions on Power Systems*, 31(5), 4108-4117.

**II.** Virasjoki, V., Siddiqui, A. S., Oliveira, F., and Salo, A. 2019. Utility-scale energy storage in an imperfectly competitive power sector. *Submitted manuscript*, 30 pages.

**III.** Virasjoki, V., Siddiqui, A. S., Zakeri, B., and Salo, A. 2018. Market power with combined heat and power production in the Nordic energy system. *IEEE Transactions on Power Systems*, 33(5), 5263-5275.

**IV.** Zakeri, B., Virasjoki, V., Syri, S., Connolly, D., Mathiesen, B., V., and Welsch, M. 2016. Impact of Germany's energy transition on the Nordic power market – A market-based multi-region energy system model. *Energy*, 115, Part 3, 1640-1662.

# Author's Contribution

**Publication I:** Market impacts of energy storage in a transmission-constrained power system

Virasjoki is the primary author. Salo and Siddiqui proposed the topic and research questions. Virasjoki, Rocha, and Siddiqui formulated the mathematical model, whereas Virasjoki and Rocha implemented and carried out the computations for the numerical case study. Virasjoki, Rocha, and Siddiqui wrote the paper with comments from Salo.

**Publication II:** Utility-scale energy storage in an imperfectly competitive power sector

Virasjoki is the primary author. Siddiqui proposed the topic, and he and Virasjoki defined the research questions. Virasjoki formulated the mathematical model with comments from Siddiqui. Oliveira contributed specifically on the computational matters. Virasjoki implemented the model, collected the data, and computed the results. She wrote the manuscript with comments from all authors.

**Publication III:** Market power with combined heat and power production in the Nordic energy system

Virasjoki is the primary author. Virasjoki and Siddiqui formulated the research questions and the topic. Virasjoki collected data and formulated the mathematical model with comments from Siddiqui and Zakeri. Virasjoki implemented the model and carried out computations for the case study. Virasjoki took the lead in writing the paper. She and Siddiqui wrote the paper with comments from Zakeri and Salo.

**Publication IV:** Impact of Germany's energy transition on the Nordic power market – A market-based multi-region energy system model

Zakeri is the primary author. He proposed the model and research questions, and wrote the paper under the supervision of Syri. Zakeri collected data, developed the model, and made the simulations and computations with the help of Virasjoki who focused on the economic analyses, in particular. All authors contributed to the development of the modeling paradigm. They also introduced data sources from the countries of their respective affiliations, discussed and analyzed the results, and finalized the paper.

# Preface

This dissertation would not have been possible without two major factors: people who supported and believed in me, to whom I am forever thankful, and an equal education system, which has brought me so far. This journey of 4+ years has also taken a lot of discipline, work, and courage. Still, I had many moments of doubt, and it took plenty of support from others, some self-will, and the possibility to create something meaningful to keep me going. I am grateful for the experiences and expertise that I now have, however, in getting here I exceeded my limits in all possible ways – both good and bad. The glorified narrative of overcoming challenges and being a hero for it is certainly not the whole truth.

Instead of being just hard work, I saw research also as a creative and social process. Yet, often we focus only on the outcomes of our work, although multidisciplinary collaboration requires a people-centered perspective. Too often, this system compromises too much of our wellbeing to achieve success. In the end, the greatest accomplishments to me were the moments of learning and states of flow, and the realization that we are all human - therefore, bound to rely on others and never fully ready.

To acknowledge the support I have received, I would first like to thank my supervising Professor Ahti Salo for his optimistic outlook, energy, and for the rigorous work that he does for science. I would also like to thank my instructor, Professor Afzal Siddiqui, for sharing his methodological expertise during my doctoral studies. I am glad that we were able to collaborate albeit the long-distances and time zone differences.

Funding from the Aalto energy efficiency STEEM project for the first years of working on my dissertation was certainly crucial, as I entered energy research as a methodology-oriented outsider. Thanks to the project leader Professor Sanna Syri for often inviting me to speak in various events throughout the years. I wish to thank especially my co-author Behnam Zakeri for the valuable discussions which taught me a lot about energy technologies and industry.

I am very grateful to Paula Rocha for coming along for the first months of writing the first paper of this dissertation; that time taught me the first steps on how research collaboration is conducted efficiently, yet humanely and meaningfully. I deeply appreciate professor Fabricio Oliveira for sharing his time and expertise during the final sprint of this spring when I was almost losing the sight at the end of the tunnel – his friendly advice on the other side of the corridor were the best kind of support. Meetings with my mentor Leena Sarvaranta have been invaluable in my professional growth, and I look up to her presence and strong values. I also wish to thank Professors Steven Gabriel and Sonja Wogrin for the positive and thorough pre-examination comments, which helped to improve this dissertation. Finally, thanks to KAUTE-säätiö, Tekniikan edistämissäätiö and Emil Aaltosen säätiö for financial support on this work.

I have been fortunate to collaborate and interact with a large group of colleagues in Aalto and abroad. Specifically, it has been a pleasure to collaborate with Tommi Ekholm at the final stages of my dissertation and I am grateful to have learned so much from him. I would also like to express my thanks to other researchers of STEEM, Tuomas Rintamäki in particular, as well as Verena Viskovic and Lina Reichenberg.

I would also like to highlight a few people from the Systems Analysis Laboratory. First, I wish to thank Minna Westerlund, who is an irreplaceable person at the lab – thank you for always having your door open for me to talk. Thanks to Eeva and Juuso for being great role models when I started to work here, and more recently to Antti for being an active, development-oriented person. Many thanks to my doctoral candidate colleagues and roommates throughout the years: especially Tuomas, Yrjänä, Antti, Mikko, Alessandro, Edoardo, Juho, Lucas, and Nikita – sharing this journey with you has made it a lot more fun! I wish to express my deepest gratitude to my dear friends and colleagues Suvi-Tuuli and Ellie for the empathy and support when times have been rough – people like you are the cornerstones, without which no work environment can function.

Finally, I believe that good research relies on a healthy balance with personal life. Ville, I would not have done this without your support, which has been endless and unconditional. I hope I can always be like that for you, too. My friends and family, thanks for the encouragement and for keeping me distracted enough, so I would not forget that there is a life to live.

Espoo, August 7, 2019

Vilma Virasjoki

# Contents

# List of Abbreviations

| | |
|---|---|
| CHP | Combined Heat and Power |
| $CO_2$ | Carbon Dioxide |
| DC | Direct Current |
| EPEC | Equilibrium Program with Equilibrium Constraints |
| ETS | Emissions Trading System |
| EU | European Union |
| GAMS | General Algebraic Modeling System |
| ISO | Independent System Operator |
| KKT | Karush-Kuhn-Tucker |
| LP | Linear Programming |
| MCP | Mixed Complementarity Problem |
| MILP | Mixed Integer Linear Programming |
| MIQCQP | Mixed Integer Quadratically Constrained Quadratic Programming |
| MIQP | Mixed Integer Quadratic Programing |
| MPEC | Mathematical Program with Equilibrium Constraints |
| MPPDC | Mathematical Program with Primal and Dual Constraints |
| NLP | Nonlinear Programming |
| PV | (Solar) Photovoltaic |
| QP | Quadratic Programming |
| TSO | Transmission System Operator |
| VRE | Variable Renewable Energy |
| VRES | Variable Renewable Energy Sources |

# 1. Introduction

## 1.1 Background

Energy systems are going through a disruptive transition. Changes in how energy is produced, transmitted, and consumed are driven by efforts to build a more sustainable future. Principally, sustainability refers to avoiding long-term environmental damages and originates from concerns over climate change. Measures such as the Paris agreement (UNFCCC, 2016) engage countries worldwide to take actions to limit the global temperature rise.

In the global energy system transition, the European Union (EU) has taken the lead in incentivizing a greener future with its 2020 climate & energy package. This includes targets to reduce greenhouse gas emissions from 1990 levels by 20%, and to increase the share of renewable energy in energy consumption and energy efficiency by 20% (Directive 2009/28/EC; Directive 2012/27/EU). In 2014, EU adopted a new 2030 climate & energy framework, which was revised in 2018 to respective targets of 40%, 32%, and 32.5% (Directive (EU) 2018/2001; Directive (EU) 2018/2002).

The emergence of large-scale variable renewable energy sources (VRES) is the most prominent result of these developments. Solar PV and wind power investments have dominated the global power capacity growth in 2011-2016 with 260 and 285 GW, respectively (IEA, 2017). Nonetheless, electricity is fundamentally different from most other commodities, which complicates power system planning and operations. Specifically, electricity needs to be used immediately when it is generated, because possibilities for storing electricity are limited. Yet, a balance between supply and demand is at all times required for the power system to maintain voltage and frequency, while respecting the transmission constraints and physical laws of power flows (Stoft, 2002; Wilson, 2002; Pozo et al., 2017). Furthermore, VRES are inherently intermittent, which increases the need for balancing, market coupling, and congestion management (e.g., Kunz, 2013; EC, 2015).

Thus, the transition toward sustainable generation goes hand in hand with the systemic viewpoint. For example, EU aims to implement a fully integrated energy system, the Energy Union (EC, 2015). This plan emphasizes free cross-border electricity flows and cooperation between countries to secure energy supply. It is also necessary to view the energy sector beyond electricity generation. The requirements for increased energy efficiency and competition also call for flexibility from the national (district) heating sectors, which are partly coupled to electricity generation. In fact, heating accounts for globally about 50% of total energy demand (IEA, 2014), which makes it essential for a successful energy system transition. As a part of Directive 2012/27/EU, combined heat and power production (CHP) is a plausible way to meet the higher energy efficiency targets (see also Mitridati and Pinson, 2016). Additionally, combinations of technologies, such as heat pumps, waste heat use, and storing heat, are likely to further these objectives (e.g., Lund et al., 2010).

Economically, the transition incurs a cost trade-off between supply security and sustainable but intermittent production. Simultaneously, the goal is to have competitive and economically efficient markets (cf. Koppelaar et al., 2016). Historically, the perspective of economics links to the motive to liberalize electricity markets, as has been the case in many other industries. Until 1990s, most countries had a national centrally managed power system. This means that state-owned monopolies managed vertically linked electricity generation, transmission and distribution, as well as retailing to consumers. In order to improve economic efficiency and foster technological innovations via competition, the markets have been restructured, e.g., in the EU countries, in the UK, and in the United States – with a varying success in different countries and on different stakeholders (Joskow, 2009; Hyman, 2010).

Although many electricity system designs still exist, there are liberalized wholesale markets in many companies. An (independent) system operator (ISO) is responsible for balancing the system (Wilson, 2002). The power networks remain natural monopolies handled by transmission system operators (TSOs) and distribution networks, which are regulated entities. However, the incentives of profit-maximizing companies are not per se in line with socially optimal outcomes, which the old regulated system sought to produce. Presently, policy makers, such as EU or national authorities or energy regulators, cannot alone ensure that the sustainability targets are reached. Therefore, they need to resort to indirect support mechanisms like economic or technical incentives on production and investments, or market design adjustments. Examples of such are taxes, priority grid-access, and EU's emissions trading system (ETS).

Flexibility is in the center of managing this transition. Along with market coupling, such as transmission grid expansions (Maurovich-Horvat et al., 2015; Huppmann and Egerer, 2015), and demand-side management, energy storage is at the forefront of discussion from the perspective of supply. Although electricity cannot be stored itself economically on a large scale, it can be converted into something else. Existing storage technologies include mature large-scale systems such as pumped hydro storage (95% of global capacity), but also newer emerging solutions like utility-scale batteries (DOE Global Energy Storage Database).

Nevertheless, the economic profitability of storage systems remains debatable (Schill and Kemfert, 2011; Zakeri and Syri, 2014 and 2015; Lueken and Apt, 2014). Specifically, storage can help integrate VRE as reserve capacity, support ramping, or be used for arbitrage or ancillary services such as frequency regulation (Sioshansi et al., 2012). However, it is challenging to account for many benefits simultaneously. Additionally, policies can act as barriers, because the optimal ownership of storage is not straightforward (Sioshansi et al., 2012): large-scale storage increases social welfare and benefits consumers by smoothing prices, but at the cost of producers (Schill and Kemfert, 2011). Because TSOs as monopolists and regulated entities are not generally allowed to own market assets such as storage, a merchant – or a merchant-consumer combination – may be the optimal solution (Sioshansi, 2010).

Despite the restructuring process, and the fact that VRE ownership is typically more dispersed, a few big companies own most of the conventional and dispatchable power generation capacity within national electricity sectors (Pozo et al., 2017). For example, in France and Estonia the largest generator has a market share of over 80% in electricity generation, whereas in the Nordic countries the shares are ca. 25-42% (Eurostat, 2018). Given that possibilities for storing electricity are limited, demand is rather inelastic, and supply is constrained by the transmission network, high demand and network congestion may give these companies market power (see e.g., Wilson, 2002; Bushnell, 2003; Fridolfsson and Tangerås, 2009; Pozo et al., 2017). Recent evidence also suggests that Nordic power market, Nord Pool Spot, may not be considered at all times and in all areas perfectly competitive (Tangerås & Mauritzen, 2019). Companies that exert market power influence markets to their benefit, e.g., by withholding supply to increase electricity prices. Although the antirust legislation prohibits the use of a dominant market position, such uses may be difficult to observe due to market design and infrastructure. Eventually, companies' decisions also affect whether implemented policies are successful. For instance, a company exerting market power uses storage differently from what is socially optimal in terms of scheduling and underusing storage (Bushnell, 2003; Schill and Kemfert, 2011; Sioshansi, 2010). Market power also affects storage investment sizes (Nasrolahpour et al., 2016; Siddiqui et al., 2018; Gonzalez-Romero et al., 2019). Finally, storage may even decrease social welfare (Sioshansi, 2014).

Energy systems are undergoing substantial and complex changes. In particular, the energy sector constitutes a significant industry with many impacts for sustainability due to its long-term environmental impacts. At present, this manifests mainly as the need to promote renewable energy and energy efficiency for environmental sustainability. However, the system includes multiple stakeholders with interlinked yet partially conflicting interests. The categorization in Table 1 summarizes their targets from different perspectives. Consequently, it is vital to assess how the energy system can remain secure while keeping sustainability in the spotlight, without compromising much of the market efficiency. A case in point is the flexibility that energy storage, efficient use of CHP plants, and viewing energy system as a whole can provide. Many of these aspects would be difficult, costly, or unfavorable to study empirically, including the impacts of storage on emissions (Sioshansi, 2011; Lueken and Apt, 2014), or impact of alternative policies, such as stronger market coupling (Ochoa and van Ackere, 2015). Mathematical models can help address these topics.

**Table 1.** Selected energy system targets categorized.

| Environmental | Technical | Economic | Producers' viewpoint | Consumers' viewpoint |
|---|---|---|---|---|
| - Sustainability<br>- Renewable energy<br>- Energy efficiency | - Flexibility<br>- Energy security<br>- Market integration | - Competition<br>- Low market power<br>- Market efficiency | - Profit maximization | - Low prices<br>- Social acceptance |

## 1.2 Objectives and Scope

This dissertation aims to answer research questions associated with the sustainable transition of energy markets. The attainment of sustainability is considered in the light of incentives toward higher VRE integration and higher energy efficiency; in particular, the effects that they may have on the rest of the energy system. The impacts of energy storage and efficient CHP plants to increase the flexibility of transitioning energy systems are in a particular focus. In general, we take the systems perspective and focus on interconnected power grids.

The twofold contributions consist of: (i) formulating and implementing mathematical models; (ii) using these models to study incentives and policies with case studies from the Western European and Nordic energy sectors. The aim is to provide results that help inform energy policies. Specifically, the models in this dissertation are formulated for the context of liberalized and interconnected markets. Various market assumptions in terms of competition and participants' underlying behavior are considered. In particular, the focal policy questions include the following:

1. How does the producers' market power affect the ongoing transition?
2. What are optimal energy storage investments, and how does large-scale storage affect markets?
3. What is the role of interlinked electricity and heat systems via CHP?
4. How does VRE integration affect energy systems?
5. What are some real-life implications from the formulated models?

Table 2 categorizes some of the key topics that Papers I-IV discuss and Figure 1 presents them as overlapping sets. Papers I-III focus mostly on overall market outcomes and producer's market power for of policy analysis. Paper IV represents a more detailed description of technologies and national energy sectors, with a specific focus on increasing market interconnections.

**Table 2.** Research questions in Papers I-IV.

| | 1. Market power | 2. Energy storage | 3. Energy systems | 4. VRE integration | 5. Case study |
|---|---|---|---|---|---|
| Paper I | X | X | | X | X |
| Paper II | X | X | | X | X |
| Paper III | X | (X) | X | | X |
| Paper IV | | | X | X | X |

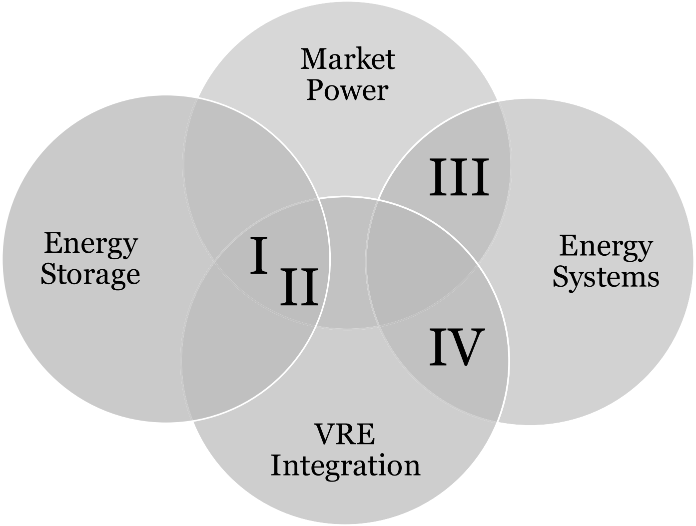

**Figure 1.** Themes of the papers.

## 1.3 Research Methods and Dissertation Structure

The mathematical models in this dissertation are based on the economic and technical aspects of energy systems. Hence, they account for the supply, demand, and the resulting market prices, as well as production and transmission. The time scales focus mainly on day-ahead markets with linkages to long-term investments and policy issues. Thus, the decisions range from the operational level of energy production, storing, and transmission, toward storage capacity acquisition.

The models in Papers I-IV are solved through optimization. Papers I and III extend the viewpoint into modeling several interlinked optimization problems through a reformulation as equilibrium or complementarity models, in which production decisions and market prices are modeled endogenously (Gabriel et al., 2013). Papers I and III consider single-level complementarity problems. Paper II employs a primal-dual approach to solve a bi-level optimization model, which are increasingly used to model energy market structures (Pozo et al., 2017). Paper IV combines optimization with simulation, resulting in a mixed-method model.

The rest of this introductory chapter is structured as follows. Section 2 presents the theoretical and methodological background of the dissertation. Section 3 discusses the results of Papers I-IV. Section 4 concludes by summarizing the contributions of the dissertation, and discusses possibilities for future research.

# 2. Methodological Background

## 2.1 Economic and Game Theoretic Concepts

Decisions in the planning of investments and operations in the energy sector can be supported with mathematical models. In particular, liberalized electricity market structures can be represented by combining concepts from microeconomics with tools of operations research, especially optimization and game theory (Pozo et al., 2017), in order to study market outcomes resulting from the market participants' decisions.

Before the electricity market liberalization, power system operations could be modeled from the viewpoint of a central planner. Mathematically, this leads to a single decision-maker's single optimization problem, such as cost minimization (Gabriel et al. 2013; Koppelaar et al., 2016). Nevertheless, in liberalized markets, the outcome results from several participants' actions. The outcome can be characterized as an equilibrium of supply and demand of multiple optimization problems. Such problems can be addressed with game theoretic concepts, which characterize them as equilibrium problems.

Perfect competition depicts a standard model for a market with a homogenous product. When the producers cannot influence the market price of a product, they act as price-takers and consider that the price is a constant (Stoft, 2002). If this applies to all producers on the supply side, the market equilibrium, i.e., the price and total quantity supplied, is equal to a single optimization problem of an independent system operator (ISO): social welfare maximization (e.g., Gabriel et al., 2013). Specifically, social welfare refers to the total surplus of the market participants, comprising both producers and consumers, and is therefore a measure of market efficiency.

Although this idealistic case is often employed in economic models, and energy market regulators seek to ensure that markets are efficient, it is not always a realistic assumption. Competition may be imperfect so that some participants can and will affect prices (Stoft, 2002; Pozo et al., 2017). This behavior is referred to as market power. Market power may occur due to various reasons, such as when only a few big companies own most of the generation capacity and they decide to withhold some production, or when there is local market power during transmission congestion (Ventosa et al., 2005). Joskow (2008) discusses imperfect competition from the viewpoint of electricity market liberalization, and Fridolfsson and Tangerås (2009), and Tangerås and Mauritzen (2019) specifically in the Nordic context.

An example of market power is the Cournot oligopoly, in which producers assess how their decisions on production quantities (supply) affect the price. By anticipating consumers' reactions (e.g., via inverse demand function) and by assuming that the other companies do not alter their supply based on their decision, each Cournot producer optimizes its production decision. The result is the Nash-Cournot equilibrium from which no producer has any incentive to deviate (see e.g., Gabriel et al., 2013). In general, this decreases the market efficiency compared to perfect competition, and worsens the position of consumers in welfare distribution.

Assuming that some producer(s) can influence the decisions of others, the corresponding model is a multi-level game of leader(s) and followers, with sequential decisions (Pozo et al., 2017). One example is a Stackelberg model in which the leader company anticipates the followers' reactions to their production decisions (Gabriel and Leuthold, 2010). Other applications in literature include investments in transmission and wind capacity (Baringo and Conejo, 2012; Maurovich-Horvat et al., 2015), power generation decisions affected by district heating dispatch (Mitridati and Pinson, 2016), setting renewable portfolio standard targets (Siddiqui et al., 2016), and investments in generation capacity as a generalized game (Centeno et al., 2011).

## 2.2 Optimization and Complementarity Modeling

In optimization a predefined objective is to be minimized (or maximized) by choosing decision variable(s) which yield the optimal solution. The solutions are usually constrained by limits, e.g., a budget or a production capacity. A general form of the classic optimization problem is

$$\min f(x) \tag{1a}$$

subject to

$$h(x) = 0 \tag{1b}$$

$$g(x) \leq 0. \tag{1c}$$

Here, $x$ is the decision variable (vector), which needs to be determined to minimize the objective $f(x)$. Depending on the forms of the equations, the optimization problem may belong to a class of, e.g., linear programming (LP), quadratic programming (QP) or non-linear programming (NLP). Additionally, if the variables are not continuous but binary or integer, the problem will be, e.g., a mixed integer linear or quadratic program (MILP/MIQP). In electricity markets, perfect competition can be modeled as a social welfare maximization problem with a quadratic objective function and (often) linear constraints on generation capacities and other technical aspects. A linear problem is convex, and a quadratic minimization problem is convex if the Hessian of the objective function is positive semi-definite, and the feasible region is convex. Therefore, such problems are relatively straightforward to solve with commercially available solvers.

If the markets are not perfectly competitive, methods other than optimization are generally needed to model energy companies' operations[1]. While each producer aims to maximize its own profits, the profits also depend on market outcomes (e.g., prices) and the decisions of other market participants. Therefore, when considering multiple producers' simultaneous optimization problems, we may talk about an equilibrium problem. If the problem is convex, we may use its first order Karush-Kuhn-Tucker (KKT) conditions, which are sufficient for global optimality. KKT conditions are written from the corresponding Lagrangian function. For optimization problem (1), this is defined as

$$\mathcal{L} = f(x) + \lambda^T h(x) + \mu^T g(x). \tag{2}$$

The Lagrangian function introduces dual variables (shadow prices) $\lambda$ and $\mu$. The corresponding KKT conditions are

$$\nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0 \tag{3a}$$
$$h(x) = 0 \tag{3b}$$
$$g(x) \leq 0 \tag{3c}$$
$$\mu^T g(x) = 0 \tag{3d}$$
$$\mu \geq 0. \tag{3e}$$

For details, refer to Gabriel et al. (2013). Thus, by writing (3c)-(3e) together, we have a complementarity condition

$$0 \leq x \perp g(x) \geq 0, \tag{4}$$

where $\perp$ means that the inner product of $x$ and $g(x)$ is zero. In a general form, we can write a complementarity problem as

$$0 \leq x \perp F(x) \geq 0, \tag{5}$$

where $F(x)$ is a vector valued function $\mathbb{R}^n \to \mathbb{R}^n$ and $x \in \mathbb{R}^n$.

Allowing also for equality conditions, such as (1b) with the corresponding dual variables being free, constitutes a mixed complementarity problem (MCP). Hence, complementarity models generalize LP, QP and NLP problems via KKT conditions. In addition, MCPs are suitable for representing problems, which cannot be represented as a single optimization problem, such as a set of conditions to hold in an equilibrium (Gabriel et al., 2013). Figure 2 illustrates how a set of interrelated optimization problems can be reformulated as a complementarity problem.

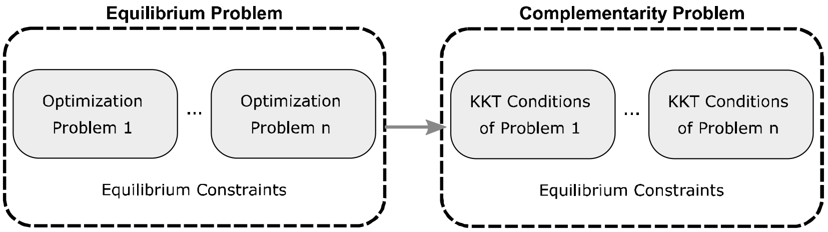

**Figure 2.** Reformulating an equilibrium problem into a complementarity problem.

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[1] Nonetheless, for instance, Cournot Oligopoly can be formulated as a single optimization problem (QP, social welfare maximization with extra quadratic cost terms), if the inverse demand function and costs are linear (cf. Hashimoto, 1985; Hobbs, 2001). This leads to the same KKT conditions as a corresponding complementarity problem of the same market. In general, the principle of symmetry is required for the result to hold (Gabriel et al., 2013).

If the optimization problems of the market participants are not simultaneous in the sense that some decision precedes or affects others, the problems are multi-, often bi-level. For example, an energy company anticipating the impact of its investment decision on the competitive market leads to a bi-level hierarchy, in which investments are on the upper level and market operations are on the lower level (e.g., Pozo et al., 2017). Bi-level models are mathematically challenging, because the lower level decisions are restricted by the solution set of the upper level, whereby the feasible region is generally non-convex. To solve models in which optimization problems are constrained by optimization problems, we may reformulate them as mathematical programs with equilibrium constraints (MPEC) for a single upper-level problem, or as equilibrium problems with equilibrium constraints (EPEC) for multiple upper-level problems.

MPECs as such are hard, because the lower level solution set (KKT conditions) is non-convex (Pozo et al., 2017). However, they can be solved via reformulations, for instance as a Mathematical Program with Primal and Dual constraints (MPPDC) (cf. Baringo and Conejo (2012) for a bi-level problem; Huppmann and Egerer (2015) for a three-stage EPEC). MPPDC presents the lower level market equilibrium via its primal and dual constraints, and the LP or QP strong duality condition, which serves to convert the problem into a convex one (cf. Dorn (1960) on QP duality and Huppmann and Egerer (2015) for the use of QP duality in an MPPDC).

Figure 3 illustrates the steps from a bi-level problem onto an MPEC or an MPPDC. Another option is to use disjunctive constraints for the lower-level KKT conditions of MPEC, which introduces new binary variables for each constraint, and results in a mixed-integer linear or quadratic program (MILP/MIQP), (cf. the Stackelberg model in Gabriel and Leuthold, 2010). A third option, also requiring the use of binary variables, are so called SOS1 (i.e., special ordered sets of type 1) variables (cf. Gabriel et al., 2013).

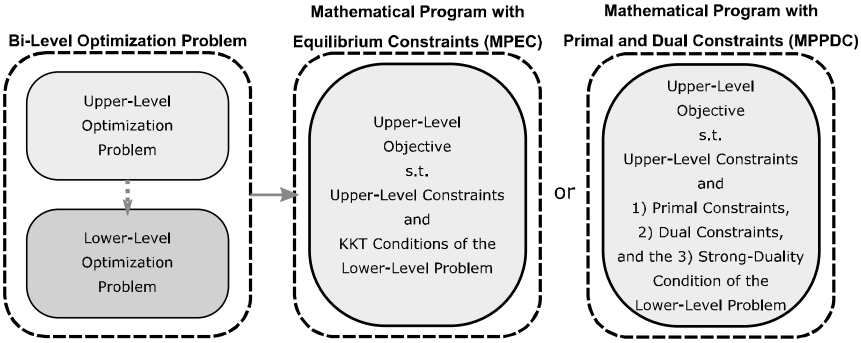

**Figure 3.** Reformulating a bi-level optimization problem equivalently either into a mathematical program with equilibrium constraints (MPEC) or a mathematical program with primal and dual constraints (MPPDC).

Overall, complementarity models can be built to represent various energy market structures due to their ability to incorporate several players' actions as well as market interactions over time and space (Gabriel et al., 2013). In particular, they permit the endogenous consideration of prices via dual variables.

Usually, it is not possible to solve the KKT conditions directly, wherefore numerical methods and software are typically used, especially when solving large-scale models.

## 2.3 Other Relevant Methodologies

Simulation is a flexible and useful method to model the behavior of market participants whose operations are not governed by single objectives at all times. Through simulation, the reality may be represented better by a logic of rules or reactions, which would be too complex to be represented by optimization or complementarity models (Ventosa et al., 2005). Simulation models can employ differential equations or agent-based behavioral algorithms. A combination of simulation and optimization methods renders a mixed-method model, called, e.g., an optimization-simulation model (e.g., Koppelaar et al., 2016).

Models also differ in terms of how they handle uncertainties (e.g., Ventosa et al., 2005). A deterministic model assumes that all information within the model is known with certainty. In the power system models of 2010's, uncertainty is typically related to VRES availability. Other possible uncertainties include the demand, prices, other companies' actions (e.g., Nasrolahpour et al., 2016) or hydro inflows. Stochastic programming is often used to account for such uncertainties (e.g., Mitridati and Pinson, 2016). This can be, for instance, in the form of scenarios with corresponding probabilities. Other methods for modeling uncertainty include sampling methods such as Monte Carlo simulation (e.g., the classifications presented by Pozo et al., 2017) or robust optimization (e.g., Zugno et al., 2016).

An alternative approach to account for temporal variations is to use a reduced time-scale technique, such as representative days (cf. Nahmmacher et al. 2016; Reichenberg et al., 2018; Reichenberg and Hedenus, 2019). By doing so, computationally intractable problems (e.g., modeling a full year of operations) can be characterized with selected, representative time periods.

# 3. Contributions of the Papers

Table 3 summarizes the research objectives, methodologies and main results of Papers I-IV. The objectives of Papers I and II are to model energy storage and market power. Both models employ a Western European case study. Paper I focuses on hourly storage operations, whereas Paper II extends the hourly market to consider storage investments as well. Paper III, too, focuses on market power, but in the context of CHP, which can be seen as a source of flexibility for the energy system. A numerical example is given for the Nordic energy system. Finally, Paper IV studies the impact of increased market coupling with higher VRE production. It presents a case study for an increased transmission capacity between Germany and the Nordic power system.

Methodologically, Papers I-III are based on optimization models, while Paper IV employs optimization-simulation. Furthermore, Papers I and III present single-level complementarity models, whereas Paper II introduces a bi-level optimization model. The temporal dimension in Papers I-IV is mostly short-term: hourly operations over a chosen time-period (the morning ramp of Paper I), a few days (Paper III), a few weeks (Paper II), or a full year (Paper IV).

Paper I accounts for uncertainty in VRE production by using a stochastic scenario tree. Paper II employs representative weeks to reduce the needed time resolution while accounting for variability in demand and VRE generation throughout the year. Finally, Paper IV uses future scenarios by varying VRE assumptions for years 2020 or 2030.

To model market coupling via cross-border electricity transmission, we have primarily used DC (direct current) load flow linearization to account for electricity flows dictated by the Kirchhoff's voltage laws in a power system. Paper I presents a congestion cost based approach similarly to Hobbs (2001), Paper II transmission as a part of ISO's problem, whereas Paper III combines DC load flow approach to DC links, as done by Bjørndal et al. (2014). Paper IV uses a transshipment method for modeling electricity transmission, which disregards more realistic loop flows and only balances differences between price areas.

The case studies presented in the Papers I-IV use mainly publicly available electricity market data based on Nord Pool, European Power Exchange (EEX), and European Network of Transmission System Operators (ENTSO-E). In addition, the case studies are based on data provided online by individual energy companies, e.g., on estimating their installed production capacity mix.

The model implementations for papers I, II and III are done by using the GAMS Software. MATLAB is used in part as data and post-processing tool, and the model presented in Paper IV is done in by MATLAB.

**Table 3.** Contributions of the papers.

| | **Research objectives** | **Methodologies** | **Main results** |
|---|---|---|---|
| Paper I:<br>Market impacts of energy storage in a transmission-constrained power system | Model the impacts of large-scale energy storage under perfect competition and Cournot Oligopoly.<br>Study the impacts in a Western European case study. | - Optimization (QP)<br>- Complementarity modeling (MCP)<br>- Stochastic scenario tree<br>- DC load flow linearization | 1. Storage reduces ramping and alleviates transmission congestion.<br>2. Market power has an impact on storage use and electricity flows.<br>3. Storage may increase $CO_2$ emissions over short term. |
| Paper II:<br>Utility-scale energy storage in an imperfectly competitive power sector | Formulate a hierarchical model to study energy storage investments with different investor objectives and different assumptions for market's competitiveness.<br>Study optimal investments in the Western European case study of Paper I. | - Optimization (QP/MIQCQP, i.e., mixed integer quadratically constrained quadratic program)<br>- Primal-dual approach for bi-level programming (MPPDC)<br>- DC load flow linearization<br>- Representative weeks via hierarchical clustering | 1. Market competition affects storage investments more than investor type.<br>2. A welfare-maximizer under perfect competition invests more capacity than a standalone merchant does, or any investor does under Cournot oligopoly.<br>3. Consumers gain most from the storage instalments; more than the investors themselves. |
| Paper III:<br>Market power with combined heat and power production in the Nordic energy system | Model market power in the context of CHP, which connects power and district heating systems.<br>Study a numerical example with Nordic energy system data. | - Optimization (QP)<br>- Complementarity modeling (MCP)<br>- DC load flow linearization with DC links | 1. CHP may enable more market power to be exercised.<br>2. Market power affects district heating generation. |
| Paper IV:<br>Impact of Germany's energy transition on the Nordic power market – a market-based multi-region energy system model | Formulate the multi-region energy system model.<br>Study the impacts of increasing VRE in Germany on the Nordic countries.<br>Study the impact of a new transmission link "NordLink" (Norway-Germany), i.e., market coupling. | - Power system optimization<br>- Simulation<br>- Scenarios for future VRE share and transmission link capacity | 1. National energy policy choices impact interconnected countries.<br>2. Energy transition slightly increases average electricity price and $CO_2$ emissions in the Nordic countries. Gains / losses from this do not affect participants equally.<br>3. The emissions and price increases subside toward 2030. |

## 3.1 Paper I

Paper I studies the market impacts of large-scale energy storage, such as pumped hydro storage. The installed capacities in such technologies are so significant that the producers' storing decisions affect the total electricity supply available at the market. This necessitates endogenous price models. Hence, we use complementarity modeling (specifically, MCPs) to represent power markets both under perfect competition and under Cournot oligopoly. This allows us to compare socially optimal markets with the case in which producers exert market power.

Unlike in the previous literature on energy storage complementarity models (e.g., Awad et al, 2014), we incorporate the combination of market power, capacity-constrained electricity transmission and VRE uncertainty. The grid is modeled as DC load flow linearization (similarly to, e.g., Hobbs, 2001). Furthermore, because energy storage is motivated by its ability to support VRE integration, the intermittency in wind and solar PV generation is modeled as a discrete scenario tree in which VRE is non-dispatchable and has priority grid access. Data for the scenario tree is based on actual VRE production in 2011 in Germany. We study the case of critical morning ramp hours. The models are applied to a Western European case study presented by Neuhoff et al. (2005), and Gabriel and Leuthold (2010), and by using updated market data from 2011 and 2014. The models and the test configurations are implemented in GAMS software and the equilibria are solved by using the PATH solver.

Our results corroborate some earlier findings on the market impacts of energy storage: for example, price smoothing over time (due to a shift in supply from scarcity to peak demand), and an increase in total welfare at the producers' expense (e.g., Schill and Kemfert, 2011). In addition, we observe a reduction in power plant ramping, which partly compensates the surplus losses of producers. From the system's viewpoint, storage also alleviates network congestion. The results for ramping and network congestion are similar under both perfect competition and Cournot oligopoly.

In line with literature (e.g., Bushnell, 2003), market power exerting producers generally underuse their storage capacity. Nonetheless, like strategic electricity production withholding, storage can also be a means to withhold production from a certain hour, e.g., in combination with more inflexible production technologies such as nuclear capacity. Consequently, the electricity flows in the studied network during the morning ramp reversed under Cournot oligopoly when comparing to the competitive case. This highlights the need to model and consider the differences between producers' strategic behavior and the behavior in line with the perfect competition assumption.

Finally, we observe that under perfect competition, energy storage may increase $CO_2$ emissions over short term. This contradicts the logic that having storage to increase the flexibility of the system would always lead to more sustainable operations. Indeed, the effect depends on the use of storage: in our case study, storage permits the use of cheaper but less flexible coal plants during the off-peak hours, whereas without it, more expensive but less polluting gas-fired units must be used to respond to the increasing demand toward the peak hours. This is similar to Lueken and Apt (2014). Interestingly, the impact is not observed for the Cournot model. In fact, the described change in the production mix and the resulting increase in emissions is socially optimal in the studied setting of 2011.

## 3.2 Paper II

Paper II extends the market-level model and Western European case study of Paper I to consider storage investments. The focus is on utility-scale battery storage investments, such as MW-scale lithium-ion storage. The main objective is to study how different investor types and the competitiveness of the underlying market affect optimal investment sizes and locations, as well as overall welfare at the market.

Understanding how different entities would invest into energy storage in addition to using storage is essential to support the shaping of future energy policies. Furthermore, energy storage investment have not been widely addressed with a bi-level models employing a realistic transmission grid, imperfect competition, and different investor objectives. For instance, Dvorkin et al. (2018) use a tri-level model with transmission to study the interactions between optimal transmission and storage investments, but imperfect competition is not considered. Gonzalez-Romero et al. (2019) study imperfect markets in their bi-level model, but the storage decisions are done by a TSO, and for a four-node test system. We build five models to consider storage decisions: a single-level optimization problem of a central planner as a benchmark, and four combinations of hierarchical structures. The lower level can be either perfectly competitive or Cournot oligopoly, which makes it possible to assess the impacts of market power. The upper-level investor can be either a welfare-maximizing entity or a standalone merchant storage operator who does not own any other assets in the markets prior to the investment decision.

The resulting four bi-level optimization models are reformulated as equivalent single-level problems by using a primal-dual approach (MPPDC). After solving for nonlinearities in the strong duality equality (cf., Baringo and Conejo, 2012) the models are reformulated as mixed integer quadratically constrained quadratic programs (MIQCQPs) with discrete storage investment options. Thus, the integer variables correspond to the sizes of selected storage as binary variables. The models are illustrated with a three-node example, whereby we note that the central planning paradigm is equal to a welfare-maximizing storage investor under perfect competition.

Nevertheless, due to numerical problems with the quadratic constraint (i.e., the strong-duality condition), the large problem instance of the Western European grid cannot be solved with our MIQCQP models. Thus, we use an iterative approach in which we decompose the investment decision from the market by enumerating all upper-level decisions and solving the lower-level quadratic programs instead. While data in Paper I corresponds to 2011 and 2014, we now update it to 2017 in Paper II. Because using the whole year for the model would be too expensive computationally, we use hierarchical clustering to create representative weeks (cf. Reichenberg et al., 2018) with a model developed by Reichenberg and Hedenus (2019). The selected four weeks have typical patterns in hourly demand and VRE generation and they are associated with corresponding weights based on how many weeks they exemplify.

Our main finding is that the underlying market condition affects optimal locations and sizes of storage investments more than the types of investors. In particular, the investments are less likely to occur, or they are located differently from what is socially optimal, if market power is exerted. A welfare-maximizer typically installs the highest capacity: under perfect competition, optimally in nuclear-dominated Belgium and France. Consumers typically gain most from the investments; even more than the investor itself does. The welfare-maximizer may even choose to take a loss from the investment under Cournot oligopoly. Our results are partly contradictory with those in Siddiqui et al. (2019). The disparity of results points to the significance of generation mix, as well as the temporal and spatial complexities of optimal investment decisions.

## 3.3 Paper III

Paper III examines the impacts of producers' market power when both electricity and heat sectors are considered jointly. In countries with a high share of district heating, CHP production creates an asymmetric interlinkage between competitive electricity markets and contract-based district heating supply. The ongoing changes in energy markets make it necessary to consider energy systems as a whole. This means that the system needs to be seen as a flexible combination of electricity and heat operations – in particular, CHP production, which also contributes to energy efficiency targets. Besides using conventional electricity generation as a source of market power (i.e., supply withholding), CHP as a dispatchable technology may provide additional leeway for big energy producers.

As in Paper I, we use complementarity modeling to represent perfectly competitive markets as well as a Cournot oligopoly. To our knowledge, the combination of electricity and heat has been rarely addressed in the complementarity modeling literature; the model by Wu and Rosen (1999) does not account for electricity transmission, market power, or VRE in any form. Furthermore, to address the research questions, we model CHP in two ways: as a status quo and as a case, where the electricity and heat production quantities are decoupled (considered as power-only or heat-only). For electricity transmission, we use both DC load flow (e.g., Hobbs, 2001), and DC links as Bjørndal et al. (2014). Our numerical example is a stylized network representing the Nordic power exchange (Nord Pool) and national district heating sectors. Specifically, we use four representative days, each for one season. We implement the models in

GAMS Software and solve them by using the quadratic programming (QP) reformulations of the MCPs to reduce computational time.[2]

The two main results of Paper III are that (i) CHP makes it possible to exercise more market power, and (ii) indirect market power from the electricity sector can shift district heating production between heat-only boilers and CHP production (specifically, increases CHP heat production for the winter season). The first finding (i) shows as a higher decrease in social welfare, a higher gain for producers, and a higher price increase than what market power enables if there is no CHP. To our understanding, this may occur if Cournot producers' withholding (reduction in production) is seen as a combination of marginal revenue from withholding (increase in price and less production costs) and marginal cost of withholding (lower sales). Then, CHP can reduce the marginal cost of withholding, because the producers can offset their lost revenue by using district heating (either heat-only facilities, or moving within the feasible operating region to an area with higher district heating production possibilities). Additionally, the increase in CHP heat (ii) may happen, because it provides more leverage for exercising market power (i.e., more available electricity generation capacity as well), especially during peak hours. Finally, we observe that even if the district heating sales are fixed, market power on the electricity sector can change the production mix of district heating and therefore, induce changes in $CO_2$ emissions.

## 3.4 Paper IV

Paper IV proposes a simulation-optimization energy system model ("Enerallt"). The model helps study the impact of market couplings in the current energy market transitions of the EU, where the markets are increasingly interconnected. At the same time, VRE increases supply uncertainty. As a case study, we address the impact of increased VRE share in Germany on the Nordic countries along with a new transmission link installment. Similar to Paper III, this model also accounts for the coupling of electricity and heat sectors in the Nordic energy system. However, Paper IV simulates the energy production operations in each country, with special focus on detailed hydropower and CHP modeling. Fundamentally, simulation is related to the lack of perfect knowledge on future circumstances, e.g., hydro inflows further ahead (in a one-year model). The electricity market operations are modeled by using optimization (hourly day-ahead operations). Power transmission is taken into account as a transshipment model. We use future scenarios to study the impact of a higher share of VRE in Germany in various combinations, for a full year in each case. These include (i) VRE capacity increase in Germany (for 2020 and 2030), (ii) NordLink transmission capacity expansion (1.4 GW between Norway and Germany), and (iii)

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[2] Although the global optimum of the corresponding QP reformulation is an equilibrium solution for the MCP (Gabriel et al., 2013; Theorem 4.4), there may be several flow solutions, e.g., due to identical marginal costs or the structure of the used test network. We have also checked ex-post that the QP solution satisfies the KKT conditions of the corresponding MCP and therefore, is an equilibrium solution.

VRE capacity increase in the Nordic countries (for 2020 or 2030). The models are implemented in MATLAB.

The paper suggests that national energy policy choices affect interconnected countries in many ways. Not only is this a consequence of building more transmission capacity, but also a result of the fit between the generation mix and production pattern characteristics of the countries. For instance, the fluctuations in VRE production and, consequently, electricity prices in Germany affect the flexibility (wind curtailment) in Denmark negatively.

We also observe that the energy transition of Germany tends to increase the average electricity price in the Nordic countries. This is because the Nordic countries are not able to fully benefit from hours with low prices in Germany, both due to limited transmission capacity, but also due to geographical correlation in wind production (especially in Denmark). As a result, the Nordic countries act as net exporters. Nonetheless, the economic gains and losses affect market participants and countries unequally. Specifically, the price increase benefits Nordic producers (especially in Norway) at the cost of consumers (especially in Sweden), who pay for the new circumstances. Additionally, the joint gain from the increased transmission and sales exceeds the loss of consumers. Mainly in Norway and Denmark, this contributes to a higher social welfare than before the energy transition and market couplings. Finally, we note that the emissions may increase temporarily, if Nordic thermal and CHP production increase to balance the price differences toward Germany.

Nevertheless, the impacts on prices, economic gains as well as emissions clearly subside and revert toward the 2014 levels in the 2030 scenario where there is more VRE in the system(s) and more transmission capacity (NordLink). Finland being the furthest away experiences weakened impacts compared with the countries that have direct transmission links to Germany.

# 4. Discussion

## 4.1 Addressing Research Gaps

Papers I-IV of this dissertation contribute primarily to the literature on energy system models. Specifically, the formulations based on optimization and complementarity modeling help assess the ongoing energy system transition. Our research questions focus on maintaining the flexibility and competitiveness of the system with more VRES and market integration. Furthermore, the models and papers serve as a basis for more elaborate models and new research questions. To some extent, the implementations of the models shed light on computational issues. Finally, they help understand complex phenomena in energy systems. Therefore, in addition to presenting mathematical formulations, each paper also presents a case study on Western European or Nordic energy systems. Thus, this dissertation aims to address effects which could be unforeseen without the use of such models.

Papers I and II provide insights into energy storage questions: hourly operations and their impacts on the rest of the markets (Paper I), and on optimal storage investment sizes and locations (Paper II). The results on economic and technical impacts and are largely in line with literature (e.g., Bushnell, 2003; Sioshansi, 2010; Schill and Kemfert, 2011), but are novel in providing more detail on ramping benefits and network alleviation, for instance. Paper II illustrates that although battery storage may not yet profitable at current installment cost levels, it would first and foremost benefit consumers, and be installed first in countries with high temporal price-variations and inflexible generation capacity.

The importance of modeling market power is evident from the results from Papers I, II, and III. In Paper I, producers that exert market power tend to use less conventional capacity and storage than price-taking companies to avoid too much price-smoothing (cf. Bushnell, 2003). However, this may not occur everywhere within the system. Instead, storage can be a way to withhold supply. In Paper I, this reverses the directions of electricity flows (i.e., the role of exporting and importing areas). Paper II shows how market power affects the sizes and locations of storage investments more than the investor's objectives. Finally, Paper III illustrates how CHP capacity can be a valuable flexibility asset for producers that exert market power.

Papers I and IV suggest how $CO_2$ emissions may increase temporarily in spite of seemingly sustainable features such as energy storage (Paper I, similarly to

Lueken and Apt, 2014) or VRE integration (Paper IV). This may happen if it is economically optimal (Paper I) or because of market coupling, if conventional generation is used to balance VRE intermittency (Paper IV). However, controversially, the undesired emissions effect of Paper I may not occur, when producers act strategically, not to maximize social welfare. Also, the $CO_2$ emissions impact of Paper IV can be expected to subside toward 2030 when the prices balance back to 2014 levels with a higher VRE share, which indicates the temporary nature of the price and emissions increases.

Papers III and IV consider the energy system more broadly by accounting for district heating production as well. Their results indicate how the systems perspective is important when assessing, for instance, the role of market power (Paper III), or economic and environmental impacts of market coupling (Paper IV). Paper IV exemplifies how differently the changes may show for countries or stakeholders.

## 4.2 Implications for Decision and Policy Making

The models and results of this dissertation provide useful viewpoints for many stakeholders in energy market planning and operations. Such practical implications are suggested, for instance, by (i) assessing and analyzing impacts of new instruments or policies, (ii) understanding the competition and interactions between market participants, or the possible impacts of market power, and (iii) determining optimal operating and investment decisions. Without mathematical modeling, many of these results would be challenging or extremely costly to identify. In major long-term projects in the energy industry, it is essential to know how the related decisions can influence the markets. In society, models can be valuable in helping decision-makers make better-informed decisions. Specifically, they can help in the evolution of welfare-maximizing, yet sustainable, secure, and fair markets in the face of ongoing global challenges such as climate change.

From the perspective of EU or national policy-makers and energy authorities, the results can support policies, such as financial or technical support instruments for new technologies. For instance, in the light of Paper I, policy-makers must consider the underlying objectives and structure of the system to avoid systemic unforeseen and unintended consequences for emissions. Policy-makers also need to consider the impact of market design: for instance, who can and should own energy storage (Papers I and II)? The impacts of market coupling also need to be assessed (Paper IV).

Energy authorities and regulators who monitor and supervise market fairness and long-term evolution can also benefit from the insights into the impacts of market power (Papers I, II, and III). If some market design incentivizes behavior which disturbs competition, regulators should be aware of this.

Although the models mainly take a system-wide viewpoint on energy markets, also individual market participants can benefit from the broader perspective. In particular, TSOs as natural monopolists can benefit from the models and their results. For instance, the impacts of storage on transmission (Paper I), the optimal sizes and locations of energy storage (Paper II), and the impact of market coupling and gains on the TSOs (Paper IV) provide valuable information for transmission operations. Specifically, such questions can affect investigations on transmission capacity investments.

Additionally, energy companies can improve their operations and investments. In general, deregulated markets and the intermittency of VRES expose companies to more uncertainty than before, which necessitates the use of decision support tools. Based on Paper II, a company could assess the impact of its storage investment on the sector as a whole. Furthermore, understanding how its competitors may behave can be strategically useful (Papers I, II, and III).

## 4.3 Model Limitations and Ethical Considerations

The models in this dissertation are stylized and aggregated in nature. Overall, their contribution is not to forecast exact market outcomes but, rather, to examine possible future scenarios and provide insights into the research questions. Toward this end, different assumptions concerning the operational strategies, available technologies, or objectives of the market participants have been employed. To ensure their representativeness and quality, the models have been calibrated based on thorough sensitivity analyses and market data. For example, Paper I discusses the effect of nuclear plant marginal costs, whereas for Paper II several representative weeks and different investment cost assumptions were tried.

The optimization problems of individual companies approximate reality. The level of market topology, as well as the generation and transmission capacities are simplified. Using a Cournot oligopoly in Papers I, II, and III instead of the more complex strategic hierarchies can to some extent overestimate the leverage of companies exerting market power. This, however, is partly taken into account by always comparing the results to the price-taking case. The temporal aspects also play a role: In Paper I, we study a short time period of ramping hours and in Paper III four seasonally representative days. The short period overlooks effects that would only occur over a longer time horizon and is not representative enough to generalize results over long periods in time. The seasonal days (Paper III) disregard extremes, because the representative days were constructed based on averages. By comparison, the representative weeks selected by hierarchical clustering in Paper II is a more justifiable approach from the temporal perspective. Similarly, simulating a full year of hourly operations (Paper IV) provides much more temporal detail.

Overall, the chosen models involve trade-offs between simplicity and representativeness. For instance, whereas Papers I-III emphasize a more strategic viewpoint over shorter time periods, Paper IV has a more detailed representation of technological features spanning several years ahead into the future. Furthermore, it is faster and easier to solve optimization problems than MCPs or MIQCQPs, and solving single-level MCPs is computationally easier than solving MPECs, not to mention EPECs. Although other more complex representations could describe reality more accurately, they are typically much harder to solve (Pozo et al., 2017). Examples include supply function equilibrium (producers bidding in price and quantity) and conjectural variation models (generalized Nash equilibrium problems with competitors' responses, cf. Centeno et al., 2011). Hence, higher complexity can make it hard to yield generalizable insights and result interpretation due to smaller size of solvable models, such as the studied time scope.

In general, data-intensive and complex operational environments require more modeling. This should put the quality and ethical issues of models into the spotlight (Wallace, 1994), because they will be increasingly important in decision-making. By definition, operations research aims to improve reality by enabling better decisions based on models which represent reality. From this perspective operations research is therefore normative and prescriptive (Carrier and Wallace, 1994). The interpretation of a model needs to be based on its purpose (Mulvey, 1994; Koppelaar et al., 2016): be it acquiring insights on a hypothetical scenario, or analyzing exact, realistic market outcomes. Nevertheless, according to Mulvey (1994), decision-makers and society prefer simplicity to more representative yet complex solutions. The same applies to policy-makers, described as model-to-policy gaps by Koppelaar et al. (2016). For transparency, it is crucial to communicate the assumptions, simplifications, worldview, limitations, strengths and purpose of the models (Wallace, 1994). Finally, the decision makers should compare the results with those suggested by other methods and models (Mulvey, 1994).

This dissertation employs different yet complementary ways of modeling energy systems and it aims to communicate the underlying assumptions clearly. For instance, choosing modeling paradigms which yield comparable results, such as in the cases of perfect competition and companies exerting market power, helps characterize a spectrum where the reality is likely to reside. This takes into account some of the uncertainty in model structure selection, i.e., that it is uncertain which kind of a model would describe reality the best. This logic applies also to the study of various scenarios (Paper IV), which provides a more informative approach than reporting just one modeled instance and the resulting outcome.

## 4.4 Avenues for Future Research

The use of models for energy system decision-making support is motivated by ongoing disruptive transition in which models can be an essential tool for building foresight. At the same time, this endeavor is affected by computational and theoretical advancements. Specifically, VRES in energy production induce more short-term fluctuations which can be accounted for through approaches such as stochastic programming, robust optimization, simulation, or decreased time resolution methods. In addition, the role of electricity in the energy palette will increase with VRE and electrification of the transport sector, as opposed to fossil fuels, boiler-based district heating and alike. This is also likely to be enhanced by policies which link markets internationally to ensure adequate energy security and transmission infrastructure. Accounting for these will lead to more complex models, but the resulting computational challenges can most likely be addressed with technical advancements.

Nevertheless, models involve always tradeoffs between detailed representations of reality and their computational burden. Therefore, there are numerous topics for future research. For instance, and in the anticipation of increasing computational possibilities, adding (VRE) uncertainty of some form in Papers III, and IV or extending the scenario tree of Paper I, appear a fruitful topic for future research. Additionally, using a more sophisticated way to construct the representative days (and using more of them) in Paper III would improve the representativeness of results. This selection of these days is more challenging than selecting geographical or technical limits, but could be done for instance by following the representative days -methods of Reichenberg et al. (2018) and Nahmmacher et al. (2016) – similar to what we use for weeks in Paper II.

Paper III could be extended by building more sophisticated models of hydrological scenarios and water values. Papers III and IV present the district heating system somewhat simplistically and ignore real electricity price areas of Norway and Sweden. Paper IV handles the energy system in more detail than Papers I-III due to its more technical emphasis; still, modeling external exports to the system in more detail (i.e., more sophisticated method for price volatility), or studying the feasibility of transmission with DC load flow or another more realistic method could be seen as improvements.

Possible extensions for Paper IV include sensitivity analyses: for example, the use of multiple starting points or various assumptions on decision rules in simulations would increase the robustness of the results. In addition, we have considered agent-based behavior for hydro and CHP producers. Therefore, a comparison to a simpler model, in which no producer would have such adaptive behavior, would provide insights on the effects of these assumptions.

Computationally and methodologically, the most promising areas for future research are related to Paper II. Due to the numerical challenges with the quadratic constraint of the MIQCQP, we were able to solve this model only for small problem instances. Therefore, decomposition methods to solve the original model would make it possible to study a wider range of investment decisions.

In addition to computational enhancements, advances in the mathematical techniques on solving EPECs would make it possible to study a wider variety of market structures in the future. For example, Paper II now considers the case of a storage-investing welfare-maximizer or merchant – a single agent. Having multiple investors (such as producers) at the upper level would render an EPEC, which would currently be computationally practically impossible to solve. As a smaller contribution, investigating an investor with market power could be a straightforward step forward. This would theoretically and computationally more burdensome than the current model, but an important viewpoint, as investment costs decrease and battery storages installments increase over time.

Finally, it is important to consider in detail how systemic and seemingly contradictory impacts, such as the increased $CO_2$ emissions in Papers I and IV, can be best understood. In Paper I, this result from the relatively short time scope, but it still highlights the importance of the emissions trading system (ETS), and the question about who should own storage in the first place (Paper II). As the price of European CO2 emissions allowances has recently significantly increased from the ca. 5 €/tonne in 2014 up to 20-25 €/t in 2019 (EEX), the emissions increase due to storage use may not be a pressing concern in Europe for the time being. From the viewpoint of Paper IV, this is a matter of the timings of the investments in the big picture, because the $CO_2$ increase in the Nordics due to German VRE is likely to balance out when more transmission capacity is built and VRE capacity increases in the Nordic countries toward 2030.

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# Publications

# Errata and Clarifications

Further to the preliminary examination process, this Section itemizes corrections and clarifications to Papers I, III and IV, whereby *Erratum* appears at the beginning of each correction.

Paper I

i. Page 4110: Binary variables for ramping decisions are not used because as an approach this would make the KKT conditions invalid. Furthermore, unit commitment decisions are not typically considered in models of the Nordic and Western Europe power markets.
ii. Page 4111: The assumption that VRE producers cannot exert market power is based on the recognition that (i) VRE owners are mostly small companies who are not in a position to influence market prices, (ii) VRE production depends on weather conditions, which would make it hard to conceal any associated market power and (iii) it is profitable to use all available VRE energy, because its marginal costs are practically zero due to the combination of feed-in-tariffs and priority grid-access.
iii. Page 4111: As in Hobbs (2001), the grid owner is assumed to be a profit-maximizer who takes transmission decisions in a system which is based on congestion fees. The question of if, and to what extent, the maximization of social welfare by the grid owner would lead to more preferred outcomes for some market stakeholders is not in the scope of this paper. This question could be answered only through significant modelling and computational efforts which are left for future research, as they would provide the foundation for a sequel paper.
iv. *Erratum*, Page 4111: “brackets” should read “round brackets”.
v. Page 4112: As shown in Fig. 4, the average wind generation in Germany is relatively stable during the four-hour period, and thus it is adequate to build a stylized scenario tree for VRE generation by using equiprobable scenarios. However, the proposed approach could be readily extended to more general settings in which these probabilities vary from one scenario to the next. The computational burden in solving these kinds of complementary models depends primarily on the number of scenarios rather than on the numerical values of their probabilities.

Paper III

i. Throughout this paper, the term *variable renewable energy* is used as a synonym for *intermittent renewable energy.*
ii. Page 5265: The references to data in the introductory Section I.A serve to motivate the general research questions in this paper. In contrast, the consolidated data in Tables III-V are employed as an input for actual modelling and computation of numerical results.

iii. Page 5266: The approach of introducing a parameter for the minimum share of district heating to be covered by heat-only is convenient for modeling purposes. In this approach, the difficulties of modeling the details of the district heating network can be avoided while still ensuring that not all district heating demand can be covered with CHP (which would be impossible due to the geographical distribution of CHP plants).

iv. Page 5266: The focus of this paper was primarily on the analysis of the impact of CHP on power markets, whereby the relatively low costs of heat storage would play a minor role. The assumption of zero operating costs for heat storage is also similar to the assumption for power storage in Paper I. At the time of writing, reliable data on the costs of heat storage were not available for this paper. Yet further analyses could be produced by employing realistic costs estimates.

v. Page 5267: The quantity of VRE production is technically a decision variable whose value is governed by weather-dependent parameters which represent conditions for generating of solar and wind power. This flexible approach is similar to that in Paper I and makes it possible to explore alternative assumptions concerning, for instance, the impacts of curtailing of VRE generation.

vi. *Erratum*, Page 5271, Figure 6: “Case 3 vs. 1” should read “DE-PC vs. SQ-PC” and “Case 4 vs. 2” should read “DE-CO vs. SQ-CO”.

vii. *Erratum*, Page 5271, Figure 7: “Case 2 vs. 1” should read “SQ-CO vs. SQ-PC” and “Case 4 vs. 3” should read “DE-CO vs. DE-PC”.

viii. *Erratum*, Page 5274, Reference [14]: Authors should be “X. Chen, C. Kang, M. O’Malley, Q. Xia, J. Bai, C. Liu, R. Sun, W. Wang, and H. Li”.

Paper IV

i. The motivation for the paper has been to combine optimization models with the added realism which can be gained by simulating how some market stakeholders are likely to behave; but this also implies that conclusive statements concerning the attainment of market equilibria can be only produced for the optimization models alone. This multi-methodology approach has nevertheless strengths in capturing behaviors which can not be readily captured through optimization models.

ii. Further topics related market coupling, most notably of the co-ordination of power exchanges and transmission system operators, have been addressed by Oggioni and Smeers (2012) who assess inefficiencies arising from the lack of integration whilst assuming price taking agents.

iii. Page 1642 and 1644: The simulation-based decision models for hydro power and CHP producers are relatively simple: for example, these models do not account for risk preferences and they also involve unrealistic assumptions about future hydro-inflows. In order to account for realistic hedging decisions, these simulation models would have to be extended by describing risk preferences while relevant future uncertainties would also have to be estimated. These extensions would lead to much more complex models and require data that is not readily available.

iv. Page 1644: For extraction plants, the area for power and heat output in Equation (10) is assumed to be convex. For backpressure plants (which are simpler than other CHP plants), there is a linear relationship between power and heat output.

v. Page 1645: The linear objective function Equation (11) leads to a cost-minimization problem which be solved with ease. It would possible to consider even non-linear convex objective functions, for instance, in order to examine questions of social welfare maximization or elastic demand.

vi. Page 1648: For each region, the marginal costs of power and heat generation are in this paper assumed to be the same. In reality, the costs may vary somewhat; but because the costs are primarily based on fuel costs and the markets for these are global, the differences are unlikely to vary significantly between neighboring countries in Europe. Moreover, the development of realistic models containing different marginal costs would be complicated by the difficulties of obtaining regional data.

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