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# Market impacts of storage in a transmission-constrained power system

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology in the Degree Programme in Engineering Physics and Mathematics.

Espoo, November 17, 2014

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ABSTRACT OF MASTER'S THESIS

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During the past few decades, electricity markets have been deregulated and standards for sustainability have increased. Consequently, producers with varying degrees of market power and transmission system operators (TSOs) aim to secure and balance electricity supply with fluctuating demand while coping with intermittent renewable generation. Although electricity cannot be stored economically, technologies such as pumped hydro storage and batteries provide opportunities for improving efficiency and stability, which would increase the reliability in the grid, and reduce peak prices and greenhouse gas emissions. Thus, interest in electricity storage is increasing and its grid capacity can be expected to grow.

This thesis provides model-based results about the likely market impacts of electricity storage when the variation in the available capacity for renewable generation and transmission constraints of the grid are taken into account. It is also assumed that demand declines linearly as a function of price. These results are based on the study of market equilibrium in which several interacting market players' simultaneous optimization problems are presented. A mathematical model for hourly storage operations is formulated both for perfect competition and Cournot oligopoly, and their respective market equilibria are solved via Karush-Kuhn-Tucker (KKT) optimality conditions. Finally, a numerical analysis for a stylized Western European electricity market situation is performed by using the GAMS software.

The results suggest that electricity storage benefits society. However, who benefits the most depends on the assumptions about market power and price elasticity. All in all, storage alleviates congestion in the grid and facilitates the integration of green energy by reducing emissions from fossil fuel ramp-ups and by stabilizing supply in spite of intermittent renewable energy generation. Nevertheless, strategic producers use less storage than what would be economically efficient. Topics for future research include more extensive numerical analyses as well as analyzing long-term aspects of investments and comparing different storage technologies.

**Keywords:** complementarity modeling, electric power markets, electricity storage, perfect competition, Cournot oligopoly, GAMS

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Viime vuosikymmeninä sähkömarkkinat on vapautettu kilpailulle ja kestävän kehityksen vaatimukset ovat kasvaneet. Tämän seurauksena sähköntuottajat ja kantaverkkoyhtiöt pyrkivät turvaamaan sähkön tarjonnan tilanteessa, jossa kysyntä vaihtelee ja osa sähköstä tuotetaan kapasiteetiltaan epävarmalla uusiutuvalla energialla. Vaikka sähköä ei vielä voida varastoida taloudellisesti, pumppuvoiman ja akkujen kaltaiset teknologiat tarjoavat tehokkuus- ja vakausetuja, jotka lisäävät sähköverkon luotettavuutta, tasoittavat hintavaihteluja sekä vähentävät kasvihuonekaasupäästöjä. Siksi sekä kiinnostus sähkön varastointiin että sen kantaverkon kapasiteetin laajentamiseen ovat kasvussa.

Tämä työ tarjoaa mallintamiseen perustuvaa tietoa sähkön varastoinnin markkinavaikutuksista asetelmassa, jossa uusiutuvan energian tuotantokapasiteetin vaihtelu ja siirtoverkon rajoitukset otetaan huomioon; lisäksi oletetaan, että kysyntä vähenee suoraan suhteessa hintaan. Työssä rakennetuilla komplementäärisuusmalleilla markkinatoimijoiden väliset tasapainoehdot voidaan kuvata optimointiongelmina. Tuntitason varastotoiminnan matemaattinen malli formuloidaan sekä täydellisen kilpailun että Cournot'n oligopolin tapauksessa. Mallien tasapainoratkaisut lasketaan Karush-Kuhn-Tucker (KKT) -optimaalisuusehdoista. Lopuksi esitetään yksinkertaistettu numeerinen analyysi Länsi-Euroopan sähkömarkkinatilanteelle GAMS-ohjelmistoa käyttäen.

Tulosten valossa sähkön varastointi hyödyttää yhteiskuntaa. Se, kenelle varastoinnista on eniten hyötyä, riippuu kilpailutilanteesta ja hintajoustoa koskevista oletuksista. Kaiken kaikkiaan varastointi vähentää verkon ylikuormittumista ja tukee uusiutuvaa energiaa vähentämällä fossiilisten polttoaineiden tuotannonvaihteluista syntyviä päästöjä sekä tasoittamalla sähkön tarjontaa epävarmasta uusiutuvan energian tuotannosta huolimatta. Epätäydellisessä kilpailussa tuottajien kuitenkin todetaan varastoivan sähköä vähemmän kuin taloudellisesti olisi tehokasta. Jatkotutkimusmahdollisuuksia ovat numeeristen analyysien laajentaminen sekä pitkän aikavälin investointien ja teknologioiden vertaileminen.

**Asiasanat:** komplementäärinen mallinnus, sähkömarkkinat, sähkön varastointi, täydellinen kilpailu, Cournot'n oligopoli, GAMS

**Kieli:** Englanti

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I would have never been able to complete this and yet stay relatively sane without my closest friends and family. Special thanks to my parents Tiina and Jussi for always acknowledging my strengths and encouraging me. My little brother Vertti - whatever was at stake, I'm afraid you lost the bet... For real, you're next in line and you will find your own thing too! Finally, my dearest Ville: thank you for being my love, my best friend, my LaTeX support person, my knowledgeable discussion partner, and for making me smile even through the most difficult times. You are my rock.

Espoo, November 17, 2014

Vilma Virasjoki

# Contents

# Nomenclature

**Sets**

| | |
|---|---|
| $\mathcal{A}(s)$ | Ancestor scenarios of $s$ |
| $\mathcal{F}(s)$ | Successor scenarios of $s$ |
| $i, j \in \mathcal{I}$ | Producer companies |
| $\ell \in \mathcal{L}$ | Power lines |
| $n, nn \in \mathcal{N}$ | Nodes |
| $n' \in \mathcal{N}$ | Swing bus |
| $s, ss \in \mathcal{S}$ | Scenarios |
| $u \in \mathcal{U}$ | Power plants |

**Parameters**

| | |
|---|---|
| $B$ | Network susceptance matrix $(n, nn)$ |
| $C^{m}$ | Marginal production costs $(u)$, €/MWh |
| $C^{st}$ | Variable storage costs $(n, i)$, €/MWh |
| $C^{up}$ | Ramp-up costs of production $(u)$, €/MWh |
| $D^{int}$ | Intercept of linear inverse demand function $(s, n)$ |
| $D^{slp}$ | Slope of linear inverse demand function $(s, n)$ |
| $EI$ | Storage input efficiency |
| $ES$ | Periodic storage efficiency |
| $G^{max}$ | Maximum generation capacity $(n, i, u)$, MW |
| $G^{solar}$ | Solar generation $(s, n)$, MW |
| $G^{wind}$ | Wind generation $(s, n)$, MW |
| $H$ | Network transfer matrix $(\ell, n)$ |
| $K$ | Maximum capacity of power lines $(\ell)$, MW |

| | |
|---|---|
| $P$ | Probability of scenario $(s)$ |
| $RI$ | Rate at which storage can be charged |
| $RO$ | Rate at which storage can be discharged |
| $ST^{cap}$ | Maximum storage capacity $(n, i)$, MWh |

**Variables**

| | |
|---|---|
| $d$ | Consumption $(s, n)$, MWh |
| $g$ | Generation $(s, n, i, u)$, MWh |
| $g^{up}$ | Generation ramp-up $(s, n, i, u)$, MWh |
| $r$ | Net sales $(s, n, i)$, MWh |
| $st$ | Stored energy $(s, n, i)$, MWh |
| $stin$ | Storage charging $(s, n, i)$, MWh |
| $stout$ | Storage discharging $(s, n, i)$, MWh |
| $v$ | Voltage angle $(s, n)$ |
| $\alpha$ | Dual for node's sales constraint $(s, n)$, €/MWh |
| $\beta$ | Dual for generation capacity constraint $(s, n, i, u)$, €/MWh |
| $\eta$ | Dual for company's sales constraint $(s, n)$, €/MWh |
| $\gamma$ | Dual for slack bus constraint $(s, n)$, €/MWh |
| $\lambda$ | Dual for energy balance, market price $(s, n)$, €/MWh |
| $\lambda^{bal}$ | Dual for stored energy balance constraint $(s, n, i)$, €/MWh |
| $\lambda^{stin}$ | Dual for maximum storage charging $(s, n, i)$, €/MWh |
| $\lambda^{stout}$ | Dual for maximum storage discharging $(s, n, i)$, €/MWh |
| $\lambda^{stup}$ | Dual for reservoir maximum level $(s, n, i)$, €/MWh |
| $\lambda^{up}$ | Dual for ramp-up constraint $(s, n, i, u)$, €/MWh |
| $\overline{\mu}$ | Dual for line capacity constraint, positive $(s, \ell)$, €/MWh |
| $\underline{\mu}$ | Dual for line capacity constraint, negative $(s, \ell)$, €/MWh |

# Terms and abbreviations

| | |
|---|---|
| **AC** | Alternating Current |
| **CAES** | Compressed Air Energy Storage |
| **CC** | Cournot Competition, a form of market power |
| **CEER** | The Council of European Energy Regulators |
| **CO** | Cournot Oligopoly, imperfect market model of this thesis |
| **CP** | Complementarity Problem |
| **CS** | Consumer Surplus |
| **DC** | Direct Current |
| **DCLF** | Direct Current Load Flow model |
| **DSO** | Distribution System Operator |
| **EEX** | European Energy Exchange |
| **EIA** | U.S. Energy Information Administration |
| **ENTSO-E** | European Network of Transmission System Operators for Electricity |
| **EP** | Equilibrium Problem |
| **EPEC** | Equilibrium Problem with Equilibrium Constraints |
| **ESA** | Energy Storage Association |
| **EU27** | European Union member countries from January 2007 to July 2013 |
| **EU28** | Current 28 European Union member countries since July 2013 |
| **FESS** | Flywheel Energy Storage System |

| | |
|---|---|
| **GAMS** | General Algebraic Modeling System for mathematical programming |
| **IEA** | International Energy Agency of OECD countries |
| **KKT** | Karush-Kuhn-Tucker first order optimality conditions |
| **LCOE** | Levelized Cost of Electricity |
| **LCP** | Linear Complementarity Problem |
| **MCP** | Mixed Complementarity Problem |
| **MILP** | Mixed Integer Linear Program |
| **MPEC** | Mathematical Program with Equilibrium Constraints |
| **NCP** | Nonlinear Complementarity Problem |
| **OECD** | Organization for Economic Cooperation and Development |
| **OP** | Optimization Problem |
| **P2G** | Power-to-Gas Energy Storage |
| **PC** | Perfect Competition, social welfare maximization model in this thesis |
| **PHS** | Pumped Hydroelectric Storage |
| **POOLCO** | Centralized power market |
| **PS** | Producer Surplus |
| **PTDF** | Power Transfer Distribution Factor matrix |
| **SMES** | Superconducting Magnetic Energy Storage |
| **SW** | Social Welfare, measure of market efficiency |
| **TSO** | Transmission System Operator |
| **VI** | Variational Inequality problem |

# Chapter 1

# Introduction

## 1.1 Background and motivation

The energy sector has faced many shifts during the past few decades. This is due to reasons ranging from changes in local energy policies to technical innovations and climate change. First, the dominating trend since the 1980s has been deregulation [Gabriel et al., 2013]. Earlier on, energy and electricity industries were tightly regulated, state-owned, and vertically integrated natural monopolies, in which reliable service and profits were assured, and the real price of electricity was declining [Hyman, 2010]. However, this discouraged technical innovations and new investments, while pricing was economically inefficient. Additionally, due to technological changes, such as increased efficiency in smaller plants, economies of scale were diminished [Wilson, 2002]. Thus, it was justified to introduce liberalized energy markets to allow for a more competitive, yet supervised, market structure [Gabriel et al., 2013]. Second, post-restructuring during the 2000s, the need for sustainability has been emphasized. Environmentally, there have been numerous incentives such as public subsidies and renewable portfolio standards to move towards utilizing more renewable energy sources and novel eco-friendly technologies [Victor and Yanosek, 2011]. As a result, the combination of decreased market control and the need to attract capital in environmental investments, and national or fuel security investments, without re-introducing regulation, has led to a policymaker's dilemma [Hyman, 2010].

However, there are still many countries in which the dominant players own a significant share of the energy market. This is generally due to mergers, acquisitions, political reasons, economies of scale, or barriers to entry [Pahle et al., 2013; Wilson, 2002]. For instance, Electricité de France (EDF) still has almost a 90% market share of energy in France [Reuters, 2013]. Furthermore, Europe's dependence on the imported gas from Russia has become a source of concern in EU politics not least due to the crisis in Eastern Europe [Forbes, 2014]. Combined with limited physical transmission capacities (both nationally and cross-border), capital intensive and technologically rigid production, as well as the relatively inelastic demand for electricity, this configuration facilitates the exercise of market power [Wilson, 2002]. In other words, it allows for companies to adjust their production quantities in order to influence electricity prices in their favor. Consequently, this may regionally create undesirable energy market outcomes in the form of lower economic efficiencies and higher CO2 emissions.

Electricity differs economically from many other commodities in that it cannot be stored. In the short term, power companies, thus, need to forecast the demand in advance to produce the optimal amount of power at a certain time period. From the transmission system operator's (TSO) and also from the consumers' point of view, the produced amount needs to be sufficient so that there is a balance between demand and supply. Otherwise, the power grid's balance would be lost, which could lead to blackouts, for example. During demand peaks, plants will be at their capacities and unable to meet any additional demand. As a result, electricity needs to be bought elsewhere, which can be both expensive and also exert more load on limited network transmission lines. Furthermore, intermittency, or fluctuation in generation from renewable energy sources, is also yet to be solved, which exacerbates the problem. Altogether, there is a need for a stabilization mechanism, such as electricity storage.

Nevertheless, there are indirect ways to store electricity and utilizing this opportunity can have a significant effect on how the market operates. The most common solution is to use hydroelectric storage such as hydro reservoirs or pumped hydro storage (PHS), which can be charged during low demand periods and discharged when additional electricity is needed [Schill and Kemfert, 2011; Bushnell, 2003]. Other storage technologies include grid-connected batteries [Wang et al., 2008], compressed air [Lund and Salgi, 2009], and chemical solutions such as power to gas (P2G) [Morris, 2013] as well as an expanding number of innovative emerging solutions. To mention an example, one such solution has recently been developed by a California based Advanced Rail Energy Storage (ARES), which aims to solve today's energy crisis and help the integration of renewable energy by employing a grid-scale storage technology, in which heavy rail cars on are pushed on top of a hill and released on demand [ARES, 2014].

Due to storage's broad opportunities, interest in large-scale electricity storage is increasing, and storage grid capacity can be expected to grow [Schill and Kemfert, 2011]. First, storage can be used to substitute and support intermittent renewable energy production instead of relying on fossil fuels. Second, storage increases flexibility because it can serve as extra capacity during peak hours for conventional energy producers. This would have a price-smoothing effect, which would decrease peak prices and increase off-peak prices. This could be advantageous from the viewpoint of all market participants. Third, storage can create arbitrage opportunities, i.e., when electricity can be produced or bought during inexpensive hours and sold during the peak hours. However, the ultimate outcome, in terms of the overall beneficiary, depends on the relative changes in the prices and demand due to the price-smoothing effect. Fourth, storage operations can ease congestion resulting from transmission constraints of the electricity network. Depending on the strategic goals of the storage owners, this could then strengthen competition and diminish the effect of market power, especially during peak periods [Bushnell, 2003]. All in all, storage utilization could affect energy markets considerably depending on market conditions.

## 1.2 Research objectives

This thesis studies the impacts of electricity storage in connection with intermittent renewable energy generation on electricity prices, generation, market measures, and network congestion. Additionally, the interaction between storage and market power will be examined. The motivation to study electricity storage stems from its possible benefits for securing electricity supply and integrating renewable energy. The main goal is to provide insights into and to support decision-making processes of electricity market participants and policymakers. Finally, conclusions about the long-term effects of storage are drawn and suggestions for future research are provided.

Some conclusions about the effects of electricity storage have been made in previous energy market studies involving various assumptions. For the focus and setup of this thesis, meaning primarily the novelty of a model that combines storage, network constraints, uncertain renewable generation, and a linear demand function, it can be hypothesized that similar outcomes can be observed. Thus, our main hypotheses include:

**Hypothesis 1.1** *Storage increases social welfare and consumer surplus at the expense of producer surplus.*

**Hypothesis 1.2** *Storage alleviates congestion in a transmission-constrained power system.*

**Hypothesis 1.3** *Storage is used more in perfect competition than in imperfect competition.*

**Hypothesis 1.4** *The more intermittent renewable energy generation is, the more storage increases social welfare.*

**Hypothesis 1.1** is motivated from the researches by Schill and Kemfert [2011] and by Sioshansi et al. [2009], whereas **Hypothesis 1.3** stems from the results of the studies by Schill and Kemfert [2011] and by Bushnell [2003]. In addition, **Hypotheses 1.2** and **1.4** are inspired mainly by the discussion in papers by Schill and Kemfert [2011] and by Bushnell [2003].

To study these research questions, a mathematical model for electricity storage will be formulated and analyzed. This is done subject to transmission constraints for the power grid and with time-dependent constraints for storage's dynamic behavior on an hourly scale over a typical day. The analysis is done both from a social welfare maximization perspective and, for comparison, as a complementarity model to handle a Cournot oligopoly, in which producers exert market power. In other words, the former represents a perfectly competitive and the latter an imperfectly competitive market. The market equilibria are obtained with complementarity modeling techniques via the solutions to the Karush-Kuhn-Tucker (KKT) first-order optimality conditions of the optimization problems and any equilibrium constraints.

The models do not take any stand on the technology of the storage because it is assumed that regardless of the type the results can be generalized to all large-scale systems [Schill and Kemfert, 2011]. Furthermore, in the near future there may be new technologies forthcoming, which should be recognized as a possibility. Intermittent renewable energy generation is included in both models by utilizing stochastic scenarios for wind and solar energy production. Both models are implemented in GAMS software and solved with aggregated realistic data for a Western European fifteen-node test network to gain some insights into the likely effects electricity storage.

## 1.3 Structure of the thesis

This thesis is structured as follows: Chapter 2 discusses the basics of electricity markets, complementarity modeling, and electricity storage models in recent literature, which further justifies the novelty of this work. Chapter 3 gives a short mathematical introduction to complementarity modeling followed by formulations for the social welfare model and Cournot oligopoly model. Chapter 4 presents data and results for the numerical application of both models. A sensitivity analysis is also conducted. Finally, Chapter 5 summarizes the conclusions and gives suggestions for future research.

# Chapter 2

# Modeling electricity markets

## 2.1 Elements of the electricity market

Energy and electricity are the basis of modern-day society. As an example of practice, if the main grid of Finland were to black out, the country would within hours be in state of emergency as described in a recent rep ort by the leading Finnish newspaper [Helsingin Sanomat, 2014]. Problems would concern not only electricity supply directly but also other main functions of society including disruptions of water, food, fuel supply, heating, telecommunications, and waste management. Hence, society is inextricably linked to the production of electricity in a complex manner involving producers, transmission operators and retailers combined with various national as well as international regulations and standards.

### 2.1.1 Key characteristics and trends

Economically, electricity markets are inherently incomplete because power flow cannot be perfectly monitored, and because electricity is not economically storable in large quantities [Wilson, 2002]. Electricity is a flow of electric charge and, generally, its energy can be stored in the form of an electrostatic field [Ter-Gazarian, 1994]. This type of energy storage is used in capacitors. However, capacitors are not viable for large-scale operations, such as in a power grid, due to their non-practical size requirements, and, thus, low energy capacity and short-time duration [Parfomak, 2012]. Consequently, electricity needs to be sold immediately after the production, which means that its price is volatile due to the fluctuating mismatch between supply and demand [Wilson, 2002]. Supply also varies as a consequence of bottlenecks such as power plant faults or network congestion. In addition, there is plenty of variation in demand giving rise to both and seasonal patterns.

While such physical complexities used to be handled adequately in a centralized paradigm, the deregulation of the industry has complicated its operations. Previously, power markets were often ruled by single state-owned companies, which were thought of as natural monopolies due to the benefits of having only one market operator, such as economies of scale and securing essential services [DiLorenzo, 1996]. During the past two decades, the main goal of liberalization has been to increase competition and consumer's freedom of choice because, in economic terms, monopolies are inefficient and give rise to higher prices than marginal costs - in other words, a form of imperfect competition [Wilson, 2002; Hyman, 2010]. Competition should also encourage diversification in energy sources and improve network infrastructure, which would make supply more secure.

Still, it is controversial whether the outcomes of deregulation have been only positive. In particular, in spite of this, there have been signs of market power being exerted by large power companies, who are in a position to influence the market price indirectly through their production and investment decisions [Gabriel et al., 2013]. In addition, although power companies can now be said to operate economically more effectively, this has not been observed to deliver any more benefits to consumers than the regulated model in the US and in the UK. Furthermore, deregulated markets seem less attractive for long-term investments, and investments in security or environmental requirements [Hyman, 2010]. All in all, deregulation can be said to achieve perfect competition if at least the following objectives are met: suppliers are price takers, there is transparency on the market price, and the production costs can be characterized as well-behaved (i.e. convex, so that marginal costs increase with output, and the average costs only decrease up to a certain, moderate size of suppliers) [Stoft, 2002].

For over a decade, this has meant requirements for transparency, nondiscrimination, regulatory oversight, and harmonized market practices in the European Union [CEER, 2014]. However, liberalization has also led to substantial turmoil in previously stable electricity markets, which highlights the need for compensatory stabilization mechanisms to ensure supply. The EU also has had an objective to integrate fully national power markets of its member countries by 2014. By 2050, the EU's main targets are to meet its climate change and renewable targets and to guarantee the security of supply, competitiveness, and adequate infrastructure [CEER, 2014].

Furthermore, another challenge is that the global demand for electricity is expected to grow hand in hand with population and industry growth. According to IEA's forecast, world electricity demand could increase by over two thirds from 2011 to 2035, which would represent over half of the increase in global primary energy use. Most of this increase comes from non-OECD countries, especially China (36%), India (13%), Southeast Asia (8%) and the Middle East (6%) [IEA, 2014*b*]. IEA's forecast also states that the share of renewable generation in power generation rises from 20% to 31% from 2011 and 2035. In the near future, this will require investments both in production capacity as well as in infrastructure. Nevertheless, at the national level, the effects may be reversed, for instance when energy-intensive industry is moved from Western countries to countries with cheaper labor and production capabilities. In Europe, electricity consumption decreased by 0.4% in 2013 compared to 2012 due to economic slowdown and energy efficiency efforts [ENTSO-E, 2014]. Even so, from the global perspective, all environmental requirements and goals should be met in spite of the growing consumption and generation capacity.

Given this background, over the past decade considerable attention has been focused on climate change, reducing environmental risks, increasing energy efficiency, sustainability, and integrating green energy. This has led to numerous changes in national energy policies. A good example is the German energy transition called "Energiewende," which aims to increase renewable energy generation, energy efficiency, and sustainable development by actions such as the nuclear phase-out and cutting down on fossil fuel consumption [Energiewende Project - Heinrich Böll Foundation, 2014]. Another well-known example are the 20-20-20 targets of the EU to cut greenhouse gas emissions by 20% from 1990 levels, to improve energy efficiency by 20% and to raise the share of energy consumption from renewable sources to 20% by 2020 [European Commission, 2014*c*]. Nevertheless, the combination of increased standards for sustainability and the decreased control over the market due to deregulation has led to the so called policy maker's dilemma.

The increasing share of renewable energy also requires the network to be technically more flexible. In practice, this kind of a smart grid means automated operations as well as real-time information, for instance. Information should be available both to the support network operator's decision making and to help consumers to understand better and to adapt their consumption to market conditions [CEER, 2014]. This would also enable deregulated markets to become more transparent and, thus, promote the requirement of good information of prices to achieve perfect competition [Stoft, 2002].

However, the growth of green energy has until now mainly been financed by government subsidies, which are temporary and are increasingly seen as politically unsustainable [Victor and Yanosek, 2011]. Due to the related risks, costs, and duration, current policies have encouraged investors to support existing clean energy technologies over innovations that would have a better chance of competing against conventional energy production. This has led to a capacity mix that is not competitive and cannot be scaled up to meet the requirements for energy security and climate change. Instead, governments should focus on "pull" types of strategies such as taxes on pollution, shifting subsidies to competitive innovations, or re-thinking the concept of green energy, which can also include innovations in electricity storage [Victor and Yanosek, 2011].

Energy supply, the excess or scarcity of fuels in particular, includes political concerns as well. The average energy dependency rate, i.e. the share of net imports, in EU-28 countries in 2012 was over 50%, and it has increased over 10 percentage points since the 1980s [European Commission, 2014*b*]. This is especially crucial in countries like Germany which are reducing the use of primary conventional generation and yet due to non-decreasing demand becoming increasingly dependent on imports, particularly Russia's crude oil, natural gas and solid fuels. In 2012, the only European net exporters of energy were Denmark and Norway. On the other hand, small countries like Malta, Luxembourg, and Cyprus were strongly dependent on imports [European Commission, 2014*b*].

Although industry has been deregulated, increasing power demand and the energy transition have contributed to rising electricity prices during the past few years. For instance, in the U.S. residential electricity retail prices have had an annual increase of 1.4 - 10.3% from 2003 until 2014, resulting in a total increase of 61% [EIA, 2014*b*]. In the EU retail price conditions and market outcomes have been found to differ across the member countries in spite of efforts towards a uniform power market. However, the price trends are similar in nearly every EU state, with an average 4% annual residential retail electricity price growth between 2008 and 2013 [European Commission, 2014*a*; Eurostat, 2014*b*]. For industrial consumers, the increase in retail prices has been much more moderate during the past few years, recently even decreasing, as can be seen from Figure 2.1.

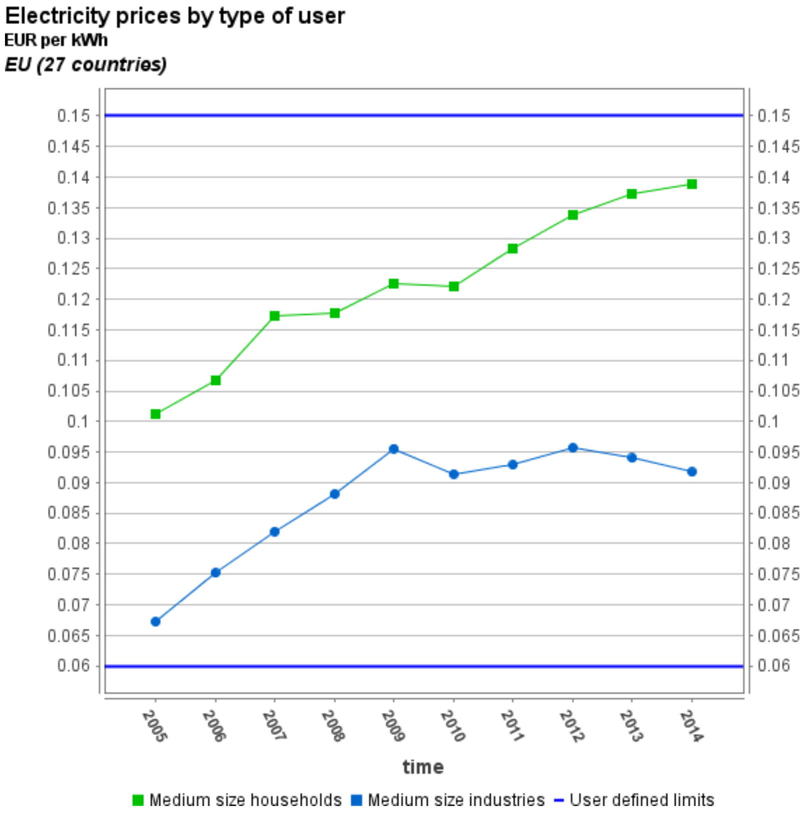


Figure 2.1: Electricity prices to final consumers on average in the EU (EU27) during 2005 - 2014 for medium sized households and industry consumers [Eurostat, 2014*b*].

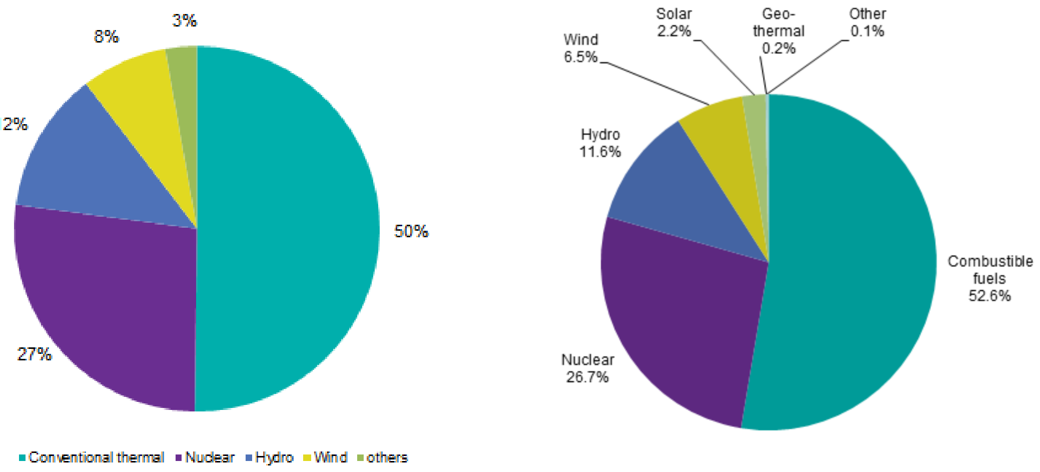
### 2.1.2 Generation

Electricity generation technologies can be divided into renewable energy sources, nuclear energy, and types that utilize fossil fuels [Sims et al., 2003]. Renewable sources such as hydro power, solar energy, wind energy, and biomass regenerate on a relatively short time scale. On the other hand, fossil fuels, such as hard coal, lignite, oil, and natural gas, require millions of years to form. Generation types also differ by their CO2 emissions, which range from high emissions of fossil fuels to relatively low or even zero emissions from renewable energy.

The yearly development of electricity generation quantities in EU-28 countries is illustrated in Figure 2.2, and the respective generation by sources in 2013 and in 2012 are presented in Figure 2.3. It can be seen that the electricity generation in EU-28 countries has slightly decreased over the past few years, with a distinct drop in 2009 due to the beginning of the financial crisis [Eurostat, 2014*c*]. In particular, generation in 2013 decreased by 1.4% compared to 2012. Both conventional generation and nuclear power decreased by 5.9% and 0.6% from 2012, respectively, although only the share of conventional generation declined, as illustrated in Figure 2.3. Additionally, even though the total generation decreased, hydropower (including pumped hydropower) and wind generation both increased by 7% and 15% [Eurostat, 2014*c*,*d*], respectively, and also grew in importance as measured by their shares of total generation in Figure 2.3. Furthermore, Figure 2.4 illustrates final electricity consumption by industry consumers, households & small-scale services, and transportation. It can be seen that although the industry demand has actually decreased over the past few years, transportation consumption has remained relatively stable, and the consumption by households and other services has had an increasing trend.

Figure 2.2: Electricity generation in EU-28 countries, 2001-2013, GWh [Eurostat, 2014*c*]. Blue line (diamonds) represents annual data and red line (squares) monthly data. As can be seen, countries report larger annual than monthly values. This happens due to various reasons: Germany, for instance, reports only main activity producers on a monthly basis, which accounts for most of the difference [Eurostat, 2014*c*].

Electricity generation is characterized by high fixed costs caused by relatively large capacity investments. Electricity generation costs are also greatly affected by economies of scale. However, the variable costs of production vary



(a) 2013

(b) 2012

Figure 2.3: Electricity generation by sources in EU-28 countries, 2013 [Eurostat, 2014*c*] and 2012 [Eurostat, 2014*d*]

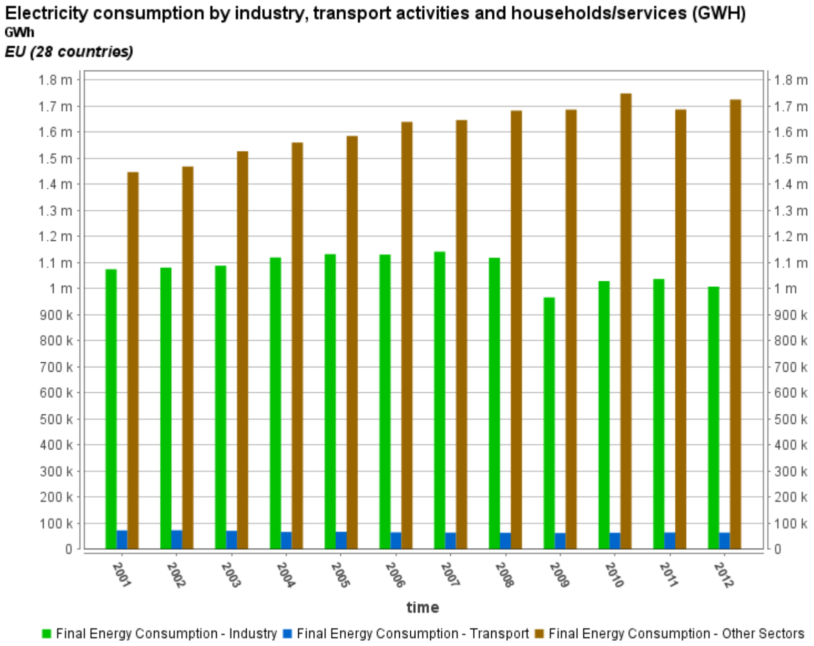


Figure 2.4: Electricity consumption in EU-28 countries, 2001-2012, GWh [Eurostat, 2014*a*].

depending on the type of energy and can be relatively low [Finnish Energy Industries and Fingrid Oyj, n.d.]. There is also plenty of variation in costs depending on location, plant type, and age [Sims et al., 2003]. A case in point, nuclear power and hydropower operate approximately at 20-25% of the variable cost of hard coal or natural gas [Schill and Kemfert, 2011]. To provide more recent costs on new generation resources, estimates for levelized capital cost, fixed and variable operations and maintenance costs, as well as total levelized cost of electricity (LCOE) as provided by EIA [2014*a*] are presented in Table 2.1. Production types also differ by the ease and expense of ramping up and down, or switching plants on and off. Again, nuclear plants are one of the slowest to ramp up with a scale of 10-20 hours in order to achieve 100% capacity from being shut down, whereas oil plants can be very quickly in full operation, in less than 2 hours [Schill and Kemfert, 2011].

Table 2.1: Estimated levelized cost of electricity (LCOE) and its components for new generation resources in the US, 2012 $/MWh for plants entering service in 2019 (without subsidies) [EIA, 2014*a*]

| **Technology** | **Levelized capital cost** | **Fixed O&M** | **Variable O&M** | **Transmission cost** | **Total LCOE** |
|---|---|---|---|---|---|
| Conventional coal | 60.0 | 4.2 | 30.3 | 1.2 | 95.6 |
| Conventional gas | 14.3 | 1.7 | 49.1 | 1.2 | 66.3 |
| Advanced nuclear | 71.4 | 11.8 | 11.8 | 1.1 | 96.1 |
| Wind | 64.1 | 13.0 | 0.0 | 3.2 | 80.3 |
| Solar photovoltaic | 114.5 | 11.4 | 0.0 | 4.1 | 130.0 |
| Hydroelectric | 72.0 | 4.1 | 6.4 | 2.0 | 84.5 |

### 2.1.3 Transmission and distribution

Electricity is transmitted from generators to customers via the power grid. It is first transported on high-voltage power lines across long distances, such as regions or countries. This is conducted by the transmission system operator (TSO), which forms a natural monopoly because it would not be sensible to build competing power grids [Finnish Energy Industries and Fingrid Oyj, n.d.]. Additionally, the TSO is responsible for the development and maintenance of the network [CEER, 2014]. The voltage is then locally reduced to medium voltage and finally to lower voltage power lines in order to convey the electricity to consumers [Finnish Energy Industries and Fingrid Oyj, n.d.]. This is handled by distribution system operators (DSO).

### 2.1.4 Retailers

Households get the electricity from their retailers, who buy the electricity from wholesale markets, i.e. from the power exchange [CEER, 2014]. Because of the deregulation of the industry, consumers in the EU can invite tenders from electricity suppliers [Finnish Energy Industries and Fingrid Oyj, n.d.]. There are currently 16 power exchanges operating in Europe [Elering, n.d.]. For example, in the Nordic countries, electricity has been traded on the Nordic power exchange, Nord Pool Spot, since the 1990s. Nord Pool Spot was the first market for trading power in the world, and, nowadays, it is also the largest of its kind [Nord Pool Spot, n.d.].

The wholesale price of electricity is determined in the power market based on the balance between supply and demand. Power is traded for most part in the day-ahead market (spot) for each hour of the following day, which closes at 12:00 CET for Nord Pool. After this, prices are calculated, trades are settled, and, from 0:00 CET onwards, power is physically delivered. However, power is also traded in real time on the intraday market to secure supply when changes occur after the spot trades have been closed. Additionally, power can be traded as financial contracts (derivatives such as futures and forward contracts) in order to hedge against risks. This being the case, no physical deliveries are made, but cash is settled [Nord Pool Spot, n.d.].

### 2.1.5 Energy storage

Energy storage helps to balance supply and demand. This may have potential benefits for the grid in terms of efficiency, which means increased reliability as well as reduced peak prices and emissions. In other words, storage can support intermittent renewable generation and serve as back up during outages. This function would smooth out prices, thereby making them less also volatile. Furthermore, conventional generation technologies are often running inefficiently caused by ramping decisions and the related ramping costs. Consequently, this is costly and often not flexible enough to meet real-time demand. Storage technologies could thus help in saving costs and many of them are also basically CO2 emission free, which supports green energy policies. Storage can also benefit producers by creating arbitrage opportunities at peak hours [ESA, 2014].

Energy storage systems cover an extensive range of technologies, which are specified in Table 2.2 as categorized by ESA [2014]; Sandia National Laboratories [2014]. Their respective shares of the energy storage projects globally are also listed based on the database of Sandia National Laboratories [2014]. Technology's share of the operational storage capacity in 2014 and operational capacity combined with planned capacity as reported in fall 2014 (including announced, contracted, under construction and offline projects) are provided. The worldwide total capacity currently rounds up to 154 GW. Moreover, it has been estimated that in order to achieve the 2 °C scenario (2DS) China, India, the EU and the US should invest at least $ 380 billion in new electricity storage by 2050, which would more than triple the currently installed storage capacity [IEA, 2014*a*].

Table 2.2: Main categories of current energy storage technologies and their shares globally.

| **Technology** | **%, operational** | **%, oper. & planned** |
|---|---:|---:|
| Pumped hydro storage | 97.6% | 96.4% |
| Thermal storage | 1.1% | 1.8% |
| Flywheel | 0.7% | 0.5% |
| Electrochemical | 0.3% | 0.5% |
| Compressed air | 0.3% | 0.7% |
| Gravitational energy storage | 0% | 0.03% |

As can be seen from Table 2.2, the most established electricity storage technology by far is pumped hydro storage (PHS) with almost 98% of the global total capacity. When looking at the planned share, it can be seen that other technologies are slowly catching up, although still far behind. In fact, hydro power has been used already for decades to balance electricity supply and is, thus, a rather mature technology. The technology is based on the gravitational energy of large water reservoirs, which are pumped full by electricity purchased during off-peak hours and discharged during peak hours [ESA, 2014]. Consequently, hydro power facilities require plenty of space and specific topographic conditions, but their operating costs are relatively low due to the almost zero costs of water [Egerer et al., 2014].

The second most common storage technology is thermal, e.g. in the temporary form of molten material or ice, which can later be utilized on heating or cooling. Flywheels (FESS) are based on storing rotational energy, and they are able to respond quickly and without interruptions to changes in demand as well as to support frequency regulation, i.e., to hold AC within its tolerance bounds [ESA, 2014]. According to Table 2.2, both compressed air (CAES) and electrochemical capacity can be expected to grow their shares in the near future. At compressed air plants, the surrounding air is stored under pressure in underground caverns and then heated and expanded on demand. Their capacities and applications are similar to those of pumped hydro. Electrochemical storage, on the other hand, converts chemical energy into electricity, such as in the case of conventional batteries. More advanced electrochemical solutions include, for instance, flow batteries, superconducting magnetic energy storage (SMES), and super capacitors, which are at an earlier stage of their development [ESA, 2014].

In addition, storage technologies can be categorized by their use, i.e., by the purpose or depending on how long they can store energy. Some are designed to account for hourly electricity shifts and others to store heat even between seasons. Apart from the larger grid-connected systems, there are also smaller-scale units, e.g., in conjunction with household solar panels [IEA, 2014*a*]. As a matter of fact, many of these systems are still unable to provide full grid-scale possibilities and some are struggling with cost-competitiveness. There are also varying policy environments, market conditions, and siting requirements, which create price distortions and mitigate storage systems' deployment [IEA, 2014*a*]. Hence, the future challenges of electricity storage lie in the economics, market design, and in the scalability and efficiency of these technologies.

## 2.2 Complementarity modeling

There is an extensive literature on complementarity modeling in energy markets. According to Gabriel et al. [2013], the fundamental motivation to use complementarity modeling stems from its flexibility for modeling various kinds of market structures that exist for energy, be it regulated, deregulated, perfect, or imperfect competition. In particular, complementarity models are able to represent simultaneous optimization problems for several interacting market players and also for several interacting markets such in the case of multicommodity models (interacting markets for substitutes or complements), storage models (interacting markets in time), or network models (interacting markets in space).

Complementarity models make it possible to handle both primal and dual variables (decision variables and prices) simultaneously, which makes them suitable for studying market equilibria. Furthermore, efficient algorithms have been developed to solve even large-scale problems so that complementarity modeling is especially useful to model realistic large-scale power line networks and interconnected markets. Consequently, complementarity modeling has become increasingly important in formulating and solving energy market models and gaining insights to support decision-making processes of market participants [Ruiz et al., 2014].

In short, complementarity problems generalize optimization problems (linear programs, convex quadratic programs, and convex nonlinear programs) but also subsume other modeling classes, which include conditions that must hold at an equilibrium, such as Nash-Cournot games. Complementarity modeling can be classified into single-level equilibrium problems such as complementarity problems and variational inequality problems (i.e., LCP, NCP, MCP and VI) and multi-level equilibrium problems, which may be reduced as mathematical programs with equilibrium constraints or equilibrium problems with equilibrium constraints (i.e., MPEC and EPEC) as long as each lower level problem is convex [Gabriel et al., 2013].

## 2.3 Strategic models in electricity markets

Hobbs [2001] discusses two Cournot models of imperfect competition that are formulated as mixed linear complementarity problems (LCP). These models represent bilateral markets both with and without arbitrage. With arbitrage, any surplus electricity is sold between the nodes, and all price differences are, thus, eliminated between the nodes. In a Cournot game, a decision maker has knowledge about the inverse demand curve, i.e., other firms' output decisions, and is able to optimize its own output with regard to them. Firms also make their production decisions independently of each other and at the same time [Gabriel et al., 2013]. As it turns out, bilateral markets with arbitrage actually result in the same outcome as centralized POOLCO markets. The model also accounts for the congestion pricing and Kirchhoff's laws. The results of a numerical example suggest that in a competitive situation prices are much lower and welfare much higher than in the Cournot cases [Hobbs, 2001].

Gabriel and Leuthold [2010] formulate a Stackelberg approach to model network constrained imperfect markets. Stackelberg approach differs from Cournot so that in addition to knowing the inverse demand curve, the leader firms are able to anticipate others' reactions to their production decisions. This defines Stackelberg as a dynamic game, in which the followers decide their output after the leader [Gabriel et al., 2013]. This is modeled as a mathematical program with equilibrium constraints (MPEC), which Gabriel and Leuthold also reformulate as a mixed-integer linear program (MILP) in order to achieve computational benefits, reliability, and the possibility to add discrete constraints. They also present a numerical fifteen-node example network of the Western European market. The results show that network effects have a significant effect on the market equilibrium when market power is present because Stackelberg leaders are not able to increase the prices until network constraints are taken into account [Gabriel and Leuthold, 2010].

Pahle et al. [2013] have recently conducted a further study utilizing complementarity modeling in electricity markets. They formulate a dynamic Cournot MCP that studies how energy investments are made under the effects of market power and CO2 emissions pricing. Furthermore, they investigate the welfare impacts under optimal CO2 pricing, which is determined by running the model with exogenously set discrete CO2 prices to find the welfare maximizing tax. Using data from the German market they find that investment levels and technology choices are affected by market power and show distinct patterns. They also claim that in most cases welfare increases as a result of CO2 tax. As for the market power assumption in regard to electricity prices and production, they note that although it is widely accepted in the literature, there is still some dispute about whether it really exists due to the lack of evidence of price manipulation or barriers to entry between the Western European countries. Therefore, they extend the concept of market power into the technological aspect by concluding that not all companies are able to invest in all technologies and, thus, exclusive access is a form of technological market power [Pahle et al., 2013].

In a recent paper by Kunz [2013], such an approach has been utilized to explain how improved congestion management could facilitate the integration of renewable energy sources in Germany. His paper discusses two methods for market-based (cost-based re-dispatching of power plants) and technical (network topology) congestion management approaches. Furthermore, the current German situation is realistically depicted as a combination of a spot market model and congestion management, either market based or technical. This represents uniform pricing, which is then compared to a nodal pricing model. The results state that there is a need for better congestion management scheme in Germany. This is justified by the fact that congestion management costs are likely to increase greatly in the future if transmission line development is not well aligned with generation infrastructure and its future investments.

## 2.4 Storage models in electricity markets

There exists some literature on how electricity storage could be utilized. Bushnell [2003] formulates a MCP Cournot model for hydroelectric reservoirs as a multiperiod scheduling problem. Model is analyzed with data from the deregulated electricity market of the Western US. Bushnell finds that the ability to store water provides companies an opportunity to exert market power so in a way which differs from the optimal solution under perfect competition. The effect is most severe during the high peak periods when smaller firms operate at their maximum capacity, and strategic companies are able to pull peak prices above competitive prices. This happens because strategic firms profit by shifting production from peak to off-peak hours. Consumer surplus decreases in Cournot competition relative to perfect competition, and this is mainly transferred to suppliers. Economic inefficiency, meaning deadweight loss and misallocation of supply to meet the demand, also increases when market power is exerted.

Schill and Kemfert [2011] develop a MCP Cournot model concerning pumped hydro storage based on German data. Their main finding is that storage is usually underutilized by strategically operating firms. Because storage tends to smooth prices, it decreases producer surpluses for companies that are involved in conventional energy production. According to Schill and Kemfert, this occurs due to a lack of coordination between the maximization of storage's arbitrage profits and conventional generation profits and due to the so-called prisoner's dilemma, when there are many strategically operating storage owners. However, an even larger increase is observed in consumer surplus, which means that the overall social welfare actually increases as a result of using storage in electricity market. Moreover, the positive overall effect is much higher when no market power is being exerted. Without any incentives for power generating companies to utilize storage, the authors conclude that in the current German electricity market strategic hydro storage is not a relevant source of market power. This can be seen as a form on market failure: storage would be beneficial for society but will be impossible to introduce if no producer would adopt it due to its negative effect on them. Nevertheless, Schill and Kemfert [2011] mention that as a policy objective to facilitate integrating renewable energy sources or in the hands of a strategic storage-only operator, the situation could be different.

Another paper, which examines the arbitrage value and welfare effects of electricity storage, has been conducted in the PJM region of Eastern US by Sioshansi et al. [2009]. First, they analyze the annual arbitrage value ($/kW-year) for a small-scale price-taking storage based on historical prices from 2002 to 2007. This is done by maximizing device's profit for a two-week planning horizon against hourly load-weighted average marginal price data, assuming perfect foresight of the prices during each two-week period. They observe that arbitrage varies due to a variety of drivers including fuel price, fuel mix, location, efficiency, device size, and hourly load profile. Most arbitrage value comes from intra-day operations with more than 50% of the theoretical maximum value derived from the first four hours. They also find that assuming perfect foresight of prices is a sufficient approximation based on a backcasting model. To be precise, using the price data of previous two weeks' in the optimization captures ca. 85% of the value of perfect foresight. Second, they study arbitrage and welfare impacts when storage capacity in the perfect competition system increases, i.e., when storage affects the market price. They state that although arbitrage reduces due to the decreased on-peak and increased off-peak prices, the optimal operation of storage is largely similar to a smaller-scale device and can, for instance, reduce congestion. In addition, large-scale storage enables improvements in consumer surplus and social welfare, albeit at the expense of producers. The authors note that this might reduce producer's incentives to invest in storage but highlight transmission owners and regulated entities as possible actors to value these social benefits.

In addition, a recent paper by Awad et al. [2014] formulates deterministic storage operations in a power grid as a MCP to determine optimal storage dispatch in connection with the market-clearing price and conventional generation. This is formulated for perfect competition combined with an incentive pricing based on the highest locational marginal price in the system. They study the impact of storage's size and location in a system of 9, 14 and 30 nodes on the prices, generation cost, storage arbitrage and consumer payment as well as provide decision making support. They observe that the larger the capacity, the smoother the prices between off-peak and peak hours. They also note that larger storage increases producer arbitrage up a certain size, while consumer payment and generation benefit reduce simultaneously. Furthermore, they state that installing storage in the transmission system instead of the distribution system due to larger price differences and installing it distributed rather than centralized may be most beneficial for storage owners.

Although there is plenty of research on energy markets and complementarity problems, the possibilities of energy storage have not yet been studied to a larger extent. Furthermore, a clear consensus about the effects of storage has not been reached. In addition, storage's effect on network congestion has not been studied until now, although it has been proven to have great significance on the market equilibrium [Gabriel and Leuthold, 2010]. This thesis aims to provide further conclusions about the effects of utilizing storage both in perfect competition and in Cournot oligopoly and thus support and enlighten the results of the previously made studies. Additionally, it introduces the possibility to study storage in the presence of network constraints combined with linear demand and uncertain renewable energy production. This aims to bring modeling closer to reality by taking into account more of the significant features of the electricity market.

# Chapter 3

# Mathematical formulation of electricity storage

Our electricity storage model is based on several modeling techniques, which will be specified in this chapter. To begin with, the model is built to represent a power line network, for which a linearized DC load flow approximation will be used. Electricity market participants are producers, a grid owner, and consumers. Their operations are included as hourly generation and storage decisions, voltage angle decisions, and demand (purchase or sales) decisions, respectively. The dynamics of these decisions are dealt with via ramping constraints for conventional generation and for storage.

Reflecting dynamic operations, the uncertainty of renewable generation will be represented as a stochastic scenario tree. Renewable generation will be included as external parameters and not as a producer's decision variables due to its special characteristics: stochasticity and priority access to the grid. Finally, network features, operational decisions, and constraints as well as the stochastic scenario tree are combined to represent optimization models of market participants. First, this is done as a social welfare maximization model, which represents perfect competition. Second, a Cournot model of profit-maximizing firms exerting market power will be formulated for comparison. Both are then constructed as complementarity problems by writing out their first-order Karush-Kuhn-Tucker (KKT) conditions together with industry-wide equilibrium constraints.

## 3.1 DC load flow model

Electricity transmission in a power network can be modeled by using linearized DC load flow (DCLF), which has many computational advantages. In practice, alternating current (AC) is approximated as direct current (DC) under a few general simplifications: neglecting reactive power and resistance, assuming that all voltage magnitudes are 1 per unit, and voltage angles on transmission lines are small [Gabriel et al., 2013; Zhang, 2010]. There are two ways to model DCLF: one is with a power transmission distribution factor (PTDF) matrix, which describes the impact of an injection or withdrawal at a specified node $n$ on all network's lines $\ell$. Another way is to use the product of voltage angle $v_n$ and network transfer matrix $H_{\ell,n}$ to account for line flow and the product of voltage angle $v_n$ and network susceptance matrix $B_{n,nn}$ to account for node flow [Gabriel and Leuthold, 2010].

Electricity transmission is governed by Kirchhoff's and Ohm's laws. In addition, linearity and superposition apply for DC load flow. This means that the power flows on transmission lines are linear combinations of power injections and that those can be broken down into components [Zhang, 2010]. Thus, power flow from node $n$ to $nn$ can be written as:

$$P_{n,nn} = \frac{v_n - v_{nn}}{X_{n,nn}} \tag{3.1}$$

where $X_{n,nn}$ is series reactance of the branch from $n$ to $nn$ [Göran Andersson, 2004], referring to the opposition to a change of electric current or voltage. Assuming similar lines, i.e., the same length and the same reactance for each $\ell$, flows can be written as presented for a three-node example in Figure 3.1. This is based on the superposition theorem, which states that power flow on line $\ell$ resulting from Equation (3.1) can be divided into its linear components of different injections [Zhang, 2010]. Thus, in Figure 3.1, for example, 2/3 of the flow on the line from A to C results from the injection in A, and respectively, 1/3 results from the injection in B. This is due to the respective series reactances of the routes (A-C and B-A-C) in Equation (3.1).

Thereby, because power flow occurs on each possible route in inverse proportion to reactance, and transmission does not work point-to-point, directing electricity transfers in the power grid is complicated. This can cause major problems because the resulting "loop flows" can also occur outside of the control area of a system operator. Consequently, electricity is not owned by a single operator but market participants are entitled to make injections or withdrawals at their specific operating locations [Wilson, 2002].

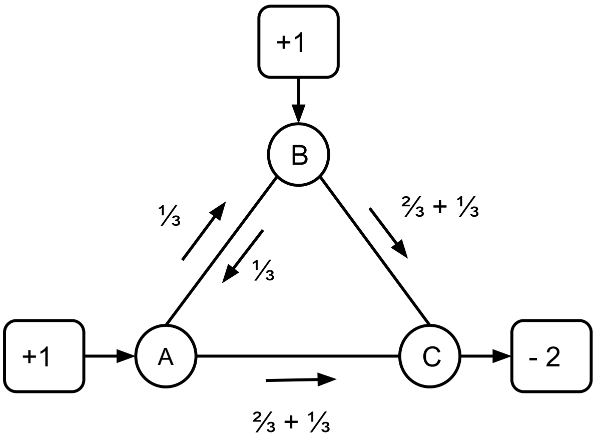


Figure 3.1: DC loop flows in a three-node example.

## 3.2 Stochastic scenarios for renewable energy

Wind energy is an important source for attaining a higher share of renewable energy production. It is characterized by its variability both by location and in time. There are distinct patterns in the generation both geographically and seasonally, especially during the year and also plenty of variation on a daily basis. Thus, the predictability of wind on a short time scale can be difficult, which has a significant effect on the integration of wind power into the electricity network [Burton et al., 2011].

Another important source of renewable energy is solar energy. Similar to wind production, there is variation but in a slightly different manner. The realized solar production differs from day to day, but it typically increases towards afternoon and decreases towards evening, until there is no generation between nightfall and sunrise. Wind generation, on the other hand, is more stochastic and less time-dependent on a daily basis. Solar production also decreases substantially during the winter months, when there is less daylight. However, wind energy does not have such a drastic change on a yearly basis, and, in Europe, it actually typically experiences higher production during the windier winter months [EEX, 2014].

A similar approach is applied for both renewable sources. Their realized production quantities are treated as external parameters for the available electricity and are, thus, not included in the decisions of the producers. This is because renewable energy benefits from a feed-in tariff and gets priority access to the power grid. In addition, generation at time $t$ is uncertain by nature, which is represented via a scenario tree. This way the generation mix can be completed in a way which is more realistic than using deterministic production, in addition to which we can simultaneously obtain insights about what happens when there is stochasticity in the grid.

The scenario tree in Figure 3.2 is based on the one used by Daniel Huppmann and Friedrich Kunz [2011] to represent wind energy production. Time periods t5 to t8 can be interpreted as a morning interval in which focus will be on generation ramp ups to match the increasing demand given by an exogenous load curve. Each scenario $s$ on each time step $t$ is equally likely to happen, i.e., their likelihoods are uniformly distributed. There are two possible successor scenarios $\mathcal{F}(s)$ from each scenario $s$, which leads to eight possible paths for the four-hour configuration. Consequently, all paths from 1 to 8 are equally likely to happen with a probability of 0.125. The same scenario tree can be assumed for all nodes $n$ of a network as long as they are geographically close or otherwise experience similar solar and wind conditions.

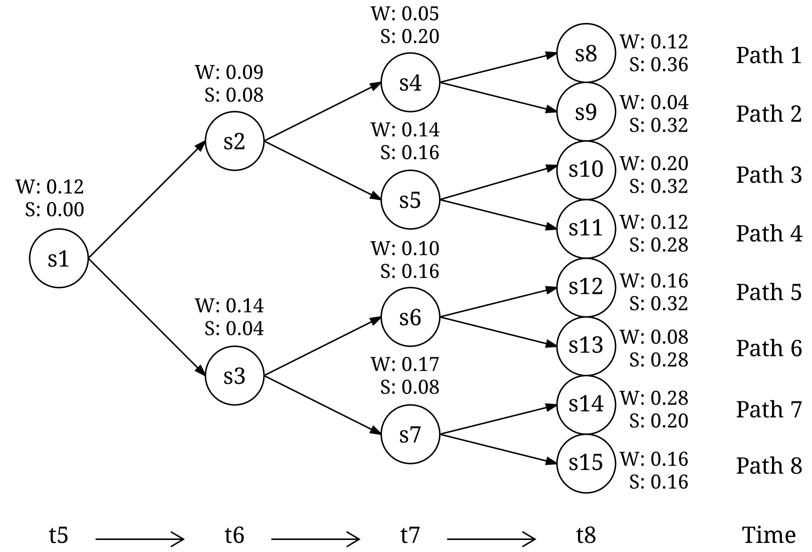


Figure 3.2: An illustration of the scenario tree representing the stochasticity of renewable energy production.

The respective numbers for each scenario $s$ in Figure 3.2 represent how much of the installed wind (W) or solar (S) production capacity is available. The capacity changes discretely at every hour. Generation capacities are stylized to represent the average pattern in Germany based on the data from EEX [2014] and a wind energy report by Pfaffel et al. [2012]. A summer month is assumed in order to have solar generation at morning hours. Capacities are set so that there is approximately zero correlation between the solar and wind production across all scenarios. However, a small negative correlation of approximately -0.2 has been observed for annual data of hourly wind and solar generation in Sweden [Widén, 2011]. It is plausible to assume that this small a correlation difference does not have a significant effect on the results.

## 3.3 A mixed complementarity model

Our modeling approach relies on a single-level mixed complementarity problem. This is assumed to be sufficient because our model will not include sub-level equilibrium conditions for any involved optimization problem, i.e., optimization problem constrained by a number of interrelated optimization problems (MPEC) or a joint solution of interrelated MPECs (EPEC) [Gabriel et al., 2013].

Formally, a MCP is defined as finding vectors $x \in \mathbb{R}^{n_1}$ and $y \in \mathbb{R}^{n_2}$ when $F : \mathbb{R}^n \to \mathbb{R}^n$, $F \neq 0$, such that for all $i$:

$$\begin{aligned} &1.\, F_i(x,y) \geq 0, \quad x_i \geq 0, \quad x_i \cdot F_i(x) = 0, \quad i = 1, ..., n_1 \\ &2.\, F_{j+n_1}(x,y) = 0, \quad y_j(free), \quad j = 1, ..., n_2 \end{aligned} \tag{3.2}$$

Conditions on the first row of Equation (3.2) are usually written more compactly as $0 \leq F(x) \perp x \geq 0$, where the perpendicular operator $\perp$ indicates complementarity and that the inner product of the two vectors is zero. This notation will be used in this thesis from now on. How this is linked to a general optimization problem (OP), i.e.,

$$
\begin{aligned}
& && \min_x f(x) \\
& s.t. && h(x) = 0 \\
& && g(x) \leq 0
\end{aligned}
\tag{3.3}
$$

is obtained by writing out the first-order Karush-Kuhn-Tucker (KKT) optimality conditions, which are a special case of complementarity conditions. They are both necessary and sufficient optimality conditions for convex linear, quadratic, and non-linear problems provided that they can be meaningfully formulated [Gabriel et al., 2013]. Thus, KKT conditions lead to a globally optimal solution and they are obtained from the Lagrangian function, which is defined as

$$
\mathcal{L} = f(x) + \lambda^T h(x) + \mu^T g(x), \tag{3.4}
$$

where $f(x)$, $h(x)$, and $g(x)$ are continuously differentiable functions and multipliers $\lambda$ and $\mu$ represent so-called Lagrange multipliers (that is, shadow prices or dual variables). KKT conditions can now be written as

$$
\begin{aligned}
& \nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0 \\
& h(x) = 0 \\
& 0 \leq \mu \perp g(x) \leq 0,
\end{aligned}
\tag{3.5}
$$

where $\nabla_x$ denotes the gradient of decision variable vector $x$. Now, when both primal (variable $x$) and dual (variables $\lambda$ and $\mu$) problems are being considered (3.5) can be seen as an equilibrium problem between the optimization of the primal and the optimization of the dual problem. Thus, when looking at the corresponding KKT conditions for several optimization problems it represents an equilibrium problem, or a complementarity problem [Gabriel et al., 2013], as illustrated in Figure 3.3.

The complementarity formulation will be used to represent the simultaneous optimization problems of all market participants: producers', consumers', and a grid owner's. Additionally, the complementarity approach helps to capture other essential features of the electricity market, such as separate but interacting markets both in time and space. In other words, these are

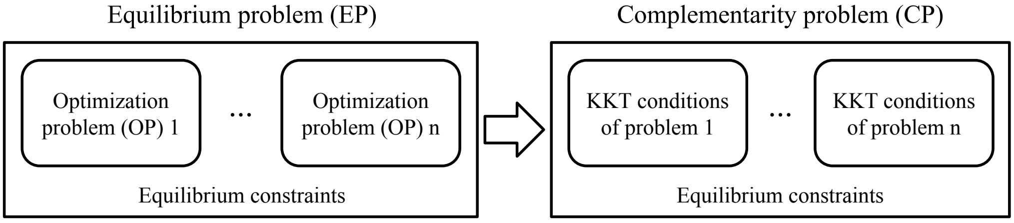


Figure 3.3: A set of optimization problems as an equilibrium problem formulated as a complementarity problem via KKT optimality conditions.

the interlinked hourly generation and storage decisions and the nodal markets in each $n$, respectively.

## 3.4 Perfect competition model

### 3.4.1 Key assumptions

Social welfare is a standard measure of market efficiency defined as the sum of consumer surplus (CS) and producer surplus (PS). It is the net gain of all participants of the market, thus also called gain from trade. Social welfare can be written as:

$$SW(q) = CS + PS = \int_0^q f_d^{-1}(q')dq' - \int_0^q f_s^{-1}(q')dq', \tag{3.6}$$

where $f_d^{-1}(q)$ is the inverse demand function and $f_s^{-1}(q)$ inverse supply functions, as illustrated in Figure 3.4. At their interception point is the economic equilibrium of price and quantity $(p^*, q^*)$.

In a perfectly competitive market all participants are price takers, i.e., they do not expect their actions to have any effect on the market price. On the other hand, the market is not perfectly competitive if some of the participants are able to affect the market price by acting strategically. The market equilibrium in a single commodity and perfect competition market can be modeled by maximizing social welfare instead of directly finding the interception point of supply and demand curves. It is also equivalent to modeling

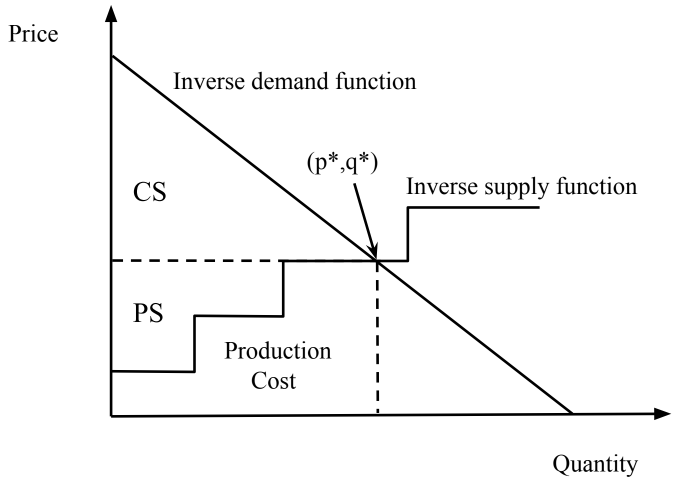


Figure 3.4: Social welfare is the sum of consumer surplus (CS) and producer surplus (PS). This area is restricted by the inverse demand function $f_d^{-1}(q)$ and inverse supply function $f_s^{-1}(q)$.

profit-maximizing firms that are price takers. This opens up many modeling techniques [Gabriel et al., 2013].

### 3.4.2 Model formulation

We will next formulate a social welfare maximization model, based on the social welfare model with a DCLF approach for the network transmission constraints as presented by Gabriel and Leuthold [2010]. Stochastic renewable generation as external parameters from a scenario tree and the ramping of conventional generation are included as in [Daniel Huppmann and Friedrich Kunz, 2011]. Furthermore, we will introduce storage into the model. See the Nomenclature section on pp. iii-iv for a full list of all sets, parameters, and variables.

To calculate social welfare (SW) (3.6), we will first write consumer and producer surpluses. Consumer surplus (CS) is determined from the integral of inverse demand function deducted by the amount that consumers actually pay. This can also be seen from Figure 3.4.

Producer surplus (PS) is obtained by summing up revenues and subtracting variable costs. When storage is available, producers make profit from both conventional generation, $g_{s,n,u}$, and the additional sales from storage, $stout_{s,n}$. Additionally, producers face variable production costs, $C_u^m$, from conventional generation, as well as from ramp-ups, $C_u^r$, and storage operations, $C_n^{st}$. An opportunity cost from storing part of the energy is taken into account as well with the component, $stin_{s,n} \cdot p^*_{s,n}$. This is because producers could choose to sell the electricity at the current market equilibrium price, and the value of choosing otherwise needs to be acknowledged.

We assume that there is one locational price for the electricity at each node $n$ and for scenario $s$, which is derived from the linear inverse demand function

$$p_{s,n} = D_{s,n}^{int} - D_{s,n}^{slp} \cdot d_{s,n}, \tag{3.7}$$

where $d_{s,n}$ is the demand quantity that corresponds to quantity $q$ of Figure 3.4. Further assumptions include that congestion is only caused if the maximum limits of the power lines are reached.

Thus, consumer and producer surpluses of each scenario $s$ can now be calculated

$$\begin{aligned} CS_s = \sum_n \int_0^{d_n *} f_d^{-1}(d'_n) dd' - \sum_n p_n^* \cdot d_n^* \\ - \sum_n p_n^* \cdot stout_n + \sum_n p_n^* \cdot stin_n \end{aligned} \tag{3.8}$$

$$\begin{aligned} PS_s = \sum_n p_n^* \cdot d_n^* + \sum_n p_n^* \cdot stout_n - \sum_n \sum_u C_u^m \cdot g_{n,u} \\ - \sum_n \sum_u C_u^{up} \cdot g_{n,u}^{up} - \sum_n C_n^{st} \cdot stout_n - \sum_n p_n^* \cdot stin_n \end{aligned} \tag{3.9}$$

Now, by substituting the equilibrium price $p_n^*$ and $f_d^{-1}$ with the linear inverse demand function (3.7) and by writing Equations (3.8) and (3.9) into the definition of social welfare (3.6), storage and revenue-related components cancel out. By writing out the objective function and its constraints, we obtain an expected minimization problem over all scenarios:

$$\begin{aligned}\min_{\substack{d,g,g^{up},v\\ stin,stout,st}} \sum_s \sum_n P_s \cdot \Big[ & \sum_u C_u^m \cdot g_{s,n,u} + \sum_u C_u^{up} \cdot g_{s,n,u}^{up} \\ & + C_n^{st} \cdot stout_{s,n} - (D_{s,n}^{int} \cdot d_{s,n} - \frac{1}{2} D_{s,n}^{slp} \cdot d_{s,n}^2) \Big]\end{aligned} \tag{3.10}$$

subject to

$$d_{s,n} - \textstyle\sum_u g_{s,n,u} - G_{s,n}^{wind} - G_{s,n}^{solar} - stout_{s,n} + stin_{s,n} + \sum_{nn} B_{n,nn} v_{s,nn} = 0$$

$$(\lambda_{s,n}, free) \qquad \forall s,n \tag{3.11a}$$

$$g_{s,n,u} \leq G_{n,u}^{max} \qquad (\beta_{s,n,u} \geq 0) \qquad \forall s,n,u \tag{3.11b}$$

$$g_{s,n,u} - g_{\mathcal{A}(s),n,u} - g_{s,n,u}^{up} \leq 0 \qquad (\lambda_{s,n,u}^{up} \geq 0) \qquad \forall s,n,u \tag{3.11c}$$

$$\sum_n H_{\ell,n} v_{s,n} \leq K_\ell \qquad (\overline{\mu}_{s,\ell} \geq 0) \qquad \forall s,\ell \tag{3.11d}$$

$$-\sum_n H_{\ell,n} v_{s,n} \leq K_\ell \qquad (\underline{\mu}_{s,\ell} \geq 0) \qquad \forall s,\ell \tag{3.11e}$$

$$v_{s,n'} = 0 \qquad (\gamma_s, free) \qquad \forall s \tag{3.11f}$$

$$st_{\mathcal{A}(s),n} \cdot ES + stin_{s,n} \cdot EI - stout_{s,n} - st_{s,n} = 0$$

$$(\lambda_{s,n}^{bal}, free) \qquad \forall s,n \tag{3.11g}$$

$$stin_{s,n} \leq RI \cdot ST_n^{cap} \qquad (\lambda_{s,n}^{stin} \geq 0) \qquad \forall s,n \tag{3.11h}$$

$$stout_{s,n} \leq RO \cdot ST_n^{cap} \qquad (\lambda_{s,n}^{stout} \geq 0) \qquad \forall s,n \tag{3.11i}$$

$$st_{s,n} \leq ST_n^{cap} \qquad (\lambda_{s,n}^{stup} \geq 0) \qquad \forall s,n \tag{3.11j}$$

$$\begin{aligned} d_{s,n}, stout_{s,n}, stin_{s,n}, st_{s,n} &\geq 0 && \forall s,n \\ g_{s,n,u}, g_{s,n,u}^{up} &\geq 0 && \forall s,n,u \\ v_{s,n}\,(free) & && \forall s,n \end{aligned}$$

Decision variables for the primal optimization model are demand, $d_{s,n}$, conventional generation, $g_{s,n,u}$, conventional generation ramp-up, $g^{up}_{s,n,u}$, voltage angle, $v_{s,n}$, and storage decisions, $stout_{s,n}, stin_{s,n}, st_{s,n}$. Each constraint (3.11a)-(3.11j) for the primal optimization problem is associated with a corresponding dual decision variable which is presented in parentheses.

Energy balance condition (3.11a) ensures that in each node $n$ and scenario $s$ the sum of electricity production from conventional technologies, wind and solar production, and storage changes is equal to the demand $d_{s,n}$. The physical grid utilization is taken into account with susceptance matrix, $B_{n,nn}$, which accounts for the electricity flow out of and into node $n$ as a DC load flow approximation. The associated dual variable, $\lambda_{s,n}$, for constraint (3.11a) defines the nodal equilibrium price, $p^{*}_{s,n}$, for electricity as defined in (3.7). Thus, in perfect competition, it also represents the marginal costs of total production, i.e. the intersection point of supply and demand curves.

Condition (3.11b) represents the maximum generation capacity, which cannot be exceeded. The ramp-up condition (3.11c), on the other hand, ensures that the generation does not exceed the generation at the previous time step, i.e., at ancestor scenario $\mathcal{A}(s)$, and the current increase in it $g^{up}_{s,n,u}$. Please note that index $u$ does not correspond to one specific power unit but to the aggregated capacity of this type in node $n$. In addition, constraints (3.11d) and (3.11e) represent the DC load flow approximation, i.e., the maximum line flows, which are calculated from the network transfer matrix $H$. Equation (3.11f) defines the slack bus, which is also needed in the network transmission calculations to avoid multiple solutions.

The remaining conditions are directly linked to storage. Equality condition (3.11g) is further energy-balance constraint, which links the stored electricity from previous time steps to the loading and discharging on each scenario. Because there are always losses related to operational inefficiency, this needs to be taken into account with efficiency parameters for each period of using storage ($ES$) and for inputs ($EI$). Constraints (3.11h) and (3.11i) limit the rate at which electricity can be charged or discharged at each time step. Furthermore, condition (3.11j) and $st_{s,n} \geq 0$ ensure that neither the minimum nor the maximum level of total storage capacity is violated.

### 3.4.3 Lagrangian function and KKT conditions

In order to solve the problem with the complementarity modeling approach, the Lagrangian function for the social welfare model (3.10)-(3.11j) is formulated and the corresponding KKT conditions of optimality are written out. For the Lagrangian function, we now obtain:

$$
\begin{aligned}
\mathcal{L} = \sum_s \sum_n P_s \cdot \Big[ & \sum_u C^m_u \cdot g_{s,n,u} + \sum_u C^{up}_u \cdot g^{up}_{s,n,u} + C^{st}_n \cdot stout_{s,n} \\
& - (D^{int}_{s,n} \cdot d_{s,n} - \frac{1}{2} D^{slp}_{s,n} \cdot d^2_{s,n}) \Big] \\
+ \sum_s \sum_n \Big[ & \lambda_{s,n} \cdot \Big( d_{s,n} - \sum_u g_{s,n,u} - G^{wind}_{s,n} - G^{solar}_{s,n} \\
& - stout_{s,n} + stin_{s,n} + \sum_{nn} B_{n,nn} v_{s,nn} \Big) \\
& + \lambda^{bal}_{s,n} \cdot \Big( st_{\mathcal{A}(s),n} \cdot ES + stin_{s,n} \cdot EI - stout_{s,n} - st_{s,n} \Big) \\
& + \lambda^{stin}_{s,n} \cdot \Big( stin_{s,n} - RI \cdot ST^{cap}_n \Big) \\
& + \lambda^{stout}_{s,n} \cdot \Big( stout_{s,n} - RO \cdot ST^{cap}_n \Big) \\
& + \lambda^{stup}_{s,n} \cdot \Big( st_{s,n} - ST^{cap}_n \Big) \Big] \\
+ \sum_s \sum_n \sum_u \Big[ & \beta_{s,n,u} \cdot \Big( g_{s,n,u} - G^{max}_{n,u} \Big) + \lambda^{up}_{s,n,u} \cdot \Big( g_{s,n,u} - g_{\mathcal{A}(s),n,u} - g^{up}_{s,n,u} \Big) \Big] \\
+ \sum_s \Big[ & \gamma_s \cdot \Big( v_{s,n'} \Big) \Big] \\
+ \sum_s \sum_\ell \Big[ & \overline{\mu}_{s,\ell} \cdot \Big( \sum_n H_{\ell,n} v_{s,n} - K_\ell \Big) + \underline{\mu}_{s,\ell} \cdot \Big( - \sum_n H_{\ell,n} v_{s,n} - K_\ell \Big) \Big]
\end{aligned}
$$

Consequently, the corresponding KKT conditions for optimality are:

$$
\begin{aligned}
& 0 \leq P_s \cdot \Big( - D^{int}_{s,n} + D^{slp}_{s,n} \cdot d_{s,n} \Big) + \lambda_{s,n} \\
& \perp d_{s,n} \geq 0 \qquad \forall s, n
\end{aligned} \tag{KKT 1}
$$

$$0 \leq P_s \cdot C_u^m - \lambda_{s,n} + \beta_{s,n,u} + \lambda_{s,n,u}^{up} - \sum_{ss \in \mathcal{F}(s)} \lambda_{ss,n,u}^{up}$$
$$\perp g_{s,n,u} \geq 0 \qquad \forall s,n,u \tag{KKT 2}$$

$$0 \leq P_s \cdot C_u^{up} - \lambda_{s,n,u}^{up}$$
$$\perp g_{s,n,u}^{up} \geq 0 \qquad \forall s,n,u \tag{KKT 3}$$

$$0 = \sum_{nn} B_{nn,n} \lambda_{s,nn} + \sum_{\ell} H_{\ell,n} \overline{\mu}_{s,\ell} - \sum_{\ell} H_{\ell,n} \underline{\mu}_{s,\ell} + \gamma_s$$
$$(v_{s,n}, free) \qquad \forall s,n \tag{KKT 4}$$

$$0 \leq \lambda_{s,n} + \lambda_{s,n}^{bal} \cdot EI + \lambda_{s,n}^{stin}$$
$$\perp stin_{s,n} \geq 0 \qquad \forall s,n \tag{KKT 5}$$

$$0 \leq P_s \cdot C_n^{st} - \lambda_{s,n} - \lambda_{s,n}^{bal} + \lambda_{s,n}^{stout}$$
$$\perp stout_{s,n} \geq 0 \qquad \forall s,n \tag{KKT 6}$$

$$0 \leq \sum_{ss \in \mathcal{F}(s)} \lambda_{ss,n}^{bal} \cdot ES - \lambda_{s,n}^{bal} + \lambda_{s,n}^{stup}$$
$$\perp st_{s,n} \geq 0 \qquad \forall s,n \tag{KKT 7}$$

$$0 = d_{s,n} - \sum_{u} g_{s,n,u} - G_{s,n}^{wind} - G_{s,n}^{solar} - stout_{s,n} + stin_{s,n} + \sum_{nn} B_{n,nn} v_{s,nn}$$
$$(\lambda_{s,n}, free) \qquad \forall s,n \tag{KKT 8}$$

$$0 \leq -g_{s,n,u} + G_{n,u}^{max}$$
$$\perp \beta_{s,n,u} \geq 0 \qquad \forall s,n,u \tag{KKT 9}$$

$$0 \leq -g_{s,n,u} + g_{\mathcal{A}(s),n,u} + g_{s,n,u}^{up}$$
$$\perp \lambda_{s,n,u}^{up} \geq 0 \qquad \forall s,n,u \tag{KKT 10}$$

$$0 \leq -\sum_n H_{\ell,n} v_{s,n} + K_\ell$$
$$\perp \overline{\mu}_{s,\ell} \geq 0 \qquad \forall s, l \tag{KKT 11}$$

$$0 \leq \sum_n H_{\ell,n} v_{s,n} + K_\ell$$
$$\perp \underline{\mu}_{s,\ell} \geq 0 \qquad \forall s, l \tag{KKT 12}$$

$$0 = v_{s,n'}$$
$$(\gamma_s, free) \qquad \forall s \tag{KKT 13}$$

$$0 = st_{\mathcal{A}(s),n} \cdot ES + stin_{s,n} \cdot EI - stout_{s,n} - st_{s,n}$$
$$(\lambda^{bal}_{s,n}, free) \qquad \forall s, n \tag{KKT 14}$$

$$0 \leq RI \cdot ST^{cap}_n - stin_{s,n}$$
$$\perp \lambda^{stin}_{s,n} \geq 0 \qquad \forall s, n \tag{KKT 15}$$

$$0 \leq RO \cdot ST^{cap}_n - stout_{s,n}$$
$$\perp \lambda^{stout}_{s,n} \geq 0 \qquad \forall s, n \tag{KKT 16}$$

$$0 \leq ST^{cap}_n - st_{s,n}$$
$$\perp \lambda^{stup}_{s,n} \geq 0 \qquad \forall s, n \tag{KKT 17}$$

## 3.5 Cournot oligopoly model

### 3.5.1 Key assumptions

Similarly to perfect competition, in an imperfectly competitive market, company $i$ has knowledge of the inverse demand curve (3.7). However, now it is also assumed to make guesses about other companies' production $g_{s,n,j,u}$, where $j \neq i$. This is because companies try to anticipate the strategic effect of their production on the market price, which in turn also depends on other companies' production quantities. Companies are assumed to produce homogenous products, and each of them chooses its production quantity simultaneously in order to maximize its own profit [Gabriel et al., 2013].

The Cournot model can now be formulated as a combination of producers' and grid owner's optimization problems, which are linked together with a market clearing condition. The resulting equilibrium of this MCP is called the Nash-Cournot equilibrium [Gabriel et al., 2013]. By definition, at a Nash equilibrium, no player would benefit from changing its decision. Here, the CO formulation is equivalent to the social welfare model apart form the strategic approach in producer's objective function. In other words, were it formulated as a perfect competition MCP, the resulting equilibrium would be the same as for maximizing social welfare [Gabriel et al., 2013].

### 3.5.2 Model formulation

#### Producer's problem

Now, each power company, $i$, solves a profit-maximization problem, which means that instead of observing node-wise demand, $d_{s,n}$, a new company-level variable, sales $r_{s,n,i}$, is introduced. This results in total sales for each node $n$ and scenario $s$ that equals to

$$\sum_{j \neq i} r_{s,n,j} + r_{s,n,i} \tag{3.12}$$

Additionally, a new variable, $\omega_{s,n}$, representing transmission fee is introduced. It is the price that the producers pay (get paid) for transmitting power from the "hub" to node $n$ (from node $n$ to the hub). The hub is operated by the grid owner, and it does not have any demand or generation. Thus, it is not included as a tangible node in the physical network. All transmission at time $t$ is assumed to be routed through the hub within one time period.

Consequently, producer $i$ aims to maximize its expected profit (equivalently, minimize negative expected profit) from its sales, storage operations, and generation as presented in (3.13). In addition to the generation, ramp-up and storage costs, which are considered similarly to the social welfare model's objective function (3.10), producers now face cost $\omega_{s,n}$ from the transmission of electricity. This must also be taken into account for the storage operations. Similarly to to perfect competition model, market price is determined from energy-balance conditions dual variables, a part of which transmission costs are, but the conditions are now in different form due to the market power assumption. Furthermore, the inverse demand curve (3.7) now depends both on the total sales as stated in (3.12) and on the available amount of renewable generation. Instead of taking the latter into account for the price establishment in a separate energy-balance condition as in the case for social welfare model, it is now included in the objective function for modeling purposes.

$$
\begin{aligned}
\min_{\substack{r,g,g^{up}\\ stin,stout,st}} \sum_{s}\sum_{n} P_s \cdot \Big[ & \sum_{u\in\mathcal{U}_{n,i}} \Big(C_u^{m} - \omega_{s,n}\Big)\cdot g_{s,n,i,u} + \sum_{u\in\mathcal{U}_{n,i}} C_u^{up}\cdot g_{s,n,i,u}^{up} \\
& + \omega_{s,n}\cdot stin_{s,n,i} + \Big(C_{n,i}^{st} - \omega_{s,n}\Big)\cdot stout_{s,n,i} \\
& - \Big(\Big(D_{s,n}^{int} - D_{s,n}^{slp}\cdot\big(\sum_{j\neq i} r_{s,n,j} + r_{s,n,i} + G_{s,n}^{wind} + G_{s,n}^{solar}\big)\Big) - \omega_{s,n}\Big) r_{s,n,i}\Big]
\end{aligned}
\tag{3.13}
$$

s.t.

$\sum_n r_{s,n,i} - \sum_n \sum_{u \in \mathcal{U}_{n,i}} g_{s,n,i,u} - \sum_n stout_{s,n,i} + \sum_n stin_{s,n,i} = 0$

$$\begin{aligned}
& & (\theta_{s,i}, free) & \quad \forall s & (3.14a)\\
& 0 \leq \sum_n r_{s,n,i} & (\eta_{s,i} \geq 0) & \quad \forall s & (3.14b)\\
& g_{s,n,i,u} \leq G^{max}_{n,i,u} & (\beta_{s,n,i,u} \geq 0) & \quad \forall s, n, u \in \mathcal{U}_{n,i} & (3.14c)\\
& g_{s,n,i,u} - g_{\mathcal{A}(s),n,i,u} - g^{up}_{s,n,i,u} \leq 0 & (\lambda^{up}_{s,n,i,u} \geq 0) & \quad \forall s, n, u \in \mathcal{U}_{n,i} & (3.14d)
\end{aligned}$$

$st_{\mathcal{A}(s),n,i} \cdot ES + stin_{s,n,i} \cdot EI - stout_{s,n,i} - st_{s,n,i} = 0$

$$\begin{aligned}
& & (\lambda^{bal}_{s,n,i}, free) & \quad \forall s, n & (3.14e)\\
& stin_{s,n,i} \leq RI \cdot ST^{cap}_{n,i} & (\lambda^{stin}_{s,n,i} \geq 0) & \quad \forall s, n & (3.14f)\\
& stout_{s,n,i} \leq RO \cdot ST^{cap}_{n,i} & (\lambda^{stout}_{s,n,i} \geq 0) & \quad \forall s, n & (3.14g)\\
& st_{s,n,i} \leq ST^{cap}_{n,i} & (\lambda^{stup}_{s,n,i} \geq 0) & \quad \forall s, n & (3.14h)
\end{aligned}$$

$$\begin{aligned}
r_{s,n,i}\,(free) & \quad \forall s, n, i\\
stout_{s,n,i}, stin_{s,n,i}, st_{s,n,i} \geq 0 & \quad \forall s, n\\
g_{s,n,i,u}, g^{up}_{s,n,i,u} \geq 0 & \quad \forall s, n, u \in \mathcal{U}_{n,i}
\end{aligned}$$

Equation (3.14a) is an energy-balance condition for each company $i$'s sales, generation and storage operations. Here, sales is defined as a free variable so it represents net sales and the total sales of company $i$ must equal its generation and storage operations. Equation (3.14b) also restricts the total sales of each company $i$ to be positive to keep balance in the grid. Other conditions are similar to those of the social welfare model (3.11a-3.11j).

### Grid owner's problem

The grid owner aims to maximize its expected profit from the transmission services that it provides for the network by choosing the voltage angle $v_{s,n}$ with costs (prices) $\omega_{s,n}$, i.e. by finding the optimal power flow. Conditions (3.16a-3.16c) are similar to those of social welfare model's (3.11a-3.11j).

$$\min_{v} \sum_{s} \sum_{n} P_s \cdot \omega_{s,n} \cdot \sum_{nn} B_{n,nn} v_{s,nn} \tag{3.15}$$

s.t.

$$\sum_{n} H_{\ell,n} v_{s,n} \leq K_\ell \qquad (\overline{\mu}_{s,\ell} \geq 0) \qquad \forall s, \ell \tag{3.16a}$$

$$-\sum_{n} H_{\ell,n} v_{s,n} \leq K_\ell \qquad (\underline{\mu}_{s,\ell} \geq 0) \qquad \forall s, \ell \tag{3.16b}$$

$$v_{s,n'} = 0 \qquad (\gamma_{s,n}, free) \qquad \forall s \tag{3.16c}$$

$$v_{s,n} \, (free) \qquad \forall s, n$$

### Market-clearing

The market-clearing condition represents the interaction between producers and consumers, and it ensures that energy balance holds for the entire network.

$$\sum_{i} r_{s,n,i} - \sum_{i} \sum_{u \in \mathcal{U}_{n,i}} g_{s,n,i,u} - \sum_{i} stout_{s,n,i} + \sum_{i} stin_{s,n,i} + \sum_{nn} B_{n,nn} v_{s,nn} = 0 \qquad (\omega_{s,n}, free) \qquad \forall s, n \tag{3.17}$$

In addition, due to the fact that sales is a free variable, a constraint to restrict the sales for each node to be positive is needed:

$$\sum_{i} r_{s,n,i} + G^{wind}_{s,n} + G^{solar}_{s,n} \geq 0 \qquad (\alpha_{s,n} \geq 0) \qquad \forall s, n \tag{3.18}$$

### 3.5.3 KKT conditions

Combining all firms' KKT conditions, grid owner's KKT conditions and the market clearing condition forms a mixed complementarity problem, and solves the Nash-Cournot equilibrium.

$$\begin{aligned} 0 = P_s \cdot \Big( - D^{int}_{s,n} + D^{slp}_{s,n} \cdot \Big( \sum_{j \neq i} r_{s,n,j} + 2 \cdot r_{s,n,i} + G^{wind}_{s,n} + G^{solar}_{s,n} \Big) + \omega_{s,n} \Big) \\ + \theta_{s,i} - \alpha_{s,n} - \eta_{s,i} \qquad (r_{s,n,i}, free) \qquad \forall s, n, i \end{aligned} \tag{KKT F1}$$

$$\begin{aligned} & 0 \leq P_s \cdot \Big( C^{m}_{u} - \omega_{s,n} \Big) - \theta_{s,i} + \beta_{s,n,i,u} + \lambda^{up}_{s,n,i,u} - \sum_{ss \in \mathcal{F}(s)} \lambda^{up}_{ss,n,i,u} \\ & \perp g_{s,n,i,u} \geq 0 \qquad \forall s, n, i, u \end{aligned} \tag{KKT F2}$$

$$\begin{aligned} & 0 \leq P_s \cdot C^{up}_{u} - \lambda^{up}_{s,n,i,u} \\ & \perp g^{up}_{s,n,i,u} \geq 0 \qquad \forall s, n, i, u \end{aligned} \tag{KKT F3}$$

$$\begin{aligned} & 0 \leq P_s \cdot \omega_{s,n} + \theta_{s,i} + \lambda^{bal}_{s,n,i} \cdot EI + \lambda^{stin}_{s,n,i} \\ & \perp stin_{s,n,i} \geq 0 \qquad \forall s, n, i \end{aligned} \tag{KKT F4}$$

$$\begin{aligned} & 0 \leq P_s \cdot \Big( C^{st}_{i} - \omega_{s,n} \Big) - \theta_{s,i} - \lambda^{bal}_{s,n,i} + \lambda^{stout}_{s,n,i} \\ & \perp stout_{s,n,i} \geq 0 \qquad \forall s, n, i \end{aligned} \tag{KKT F5}$$

$$\begin{aligned} & 0 \leq \sum_{ss \in \mathcal{F}(s)} \lambda^{bal}_{ss,n,i} \cdot ES - \lambda^{bal}_{s,n,i} + \lambda^{stup}_{s,n,i} \\ & \perp st_{s,n,i} \geq 0 \qquad \forall s, n, i \end{aligned} \tag{KKT F6}$$

$$\begin{aligned} & 0 = \sum_{n} r_{s,n,i} - \sum_{n} \sum_{u \in \mathcal{U}_{n,i}} g_{s,n,i,u} - \sum_{n} stout_{s,n,i} + \sum_{n} stin_{s,n,i} \\ & (\theta_{s,i}, free) \qquad \forall s, i \end{aligned} \tag{KKT F7}$$

$$0 \leq -g_{s,n,i,u} + G^{max}_{n,i,u}$$
$$\perp \beta_{s,n,i,u} \geq 0 \qquad \forall s, n, i, u \tag{KKT F8}$$

$$0 \leq -g_{s,n,i,u} + g_{\mathcal{A}(s),n,i,u} + g^{up}_{s,n,i,u}$$
$$\perp \lambda^{up}_{s,n,i,u} \geq 0 \qquad \forall s, n, i, u \tag{KKT F9}$$

$$0 = st_{\mathcal{A}(s),n,i} \cdot ES + stin_{s,n,i} \cdot EI - stout_{s,n,i} - st_{s,n,i}$$
$$(\lambda^{bal}_{s,n}, free) \qquad \forall s, n, i \tag{KKT F10}$$

$$0 \leq RI \cdot ST^{cap}_{n,i} - stin_{s,n,i}$$
$$\perp \lambda^{stin}_{s,n,i} \geq 0 \qquad \forall s, n, i \tag{KKT F11}$$

$$0 \leq RO \cdot ST^{cap}_{n,i} - stout_{s,n,i}$$
$$\perp \lambda^{stout}_{s,n,i} \geq 0 \qquad \forall s, n, i \tag{KKT F12}$$

$$0 \leq ST^{cap}_{n,i} - st_{s,n,i}$$
$$\perp \lambda^{stup}_{s,n,i} \geq 0 \qquad \forall s, n, i \tag{KKT F13}$$

$$0 \leq \sum_{n} r_{s,n,i}$$
$$\perp \eta_{s,i} \geq 0 \qquad \forall s, i \tag{KKT F14}$$

$$0 = \sum_{nn} P_s \cdot B_{nn,n} \omega_{s,nn} + \sum_{\ell} H_{\ell,n} \overline{\mu}_{s,\ell} - \sum_{\ell} H_{\ell,n} \underline{\mu}_{s,\ell} + \gamma_{s,n}$$
$$(v_{s,n}, free) \qquad \forall s, n \tag{KKT G1}$$

$$0 \leq -\sum_{n} H_{\ell,n} v_{s,n} + K_{\ell}$$
$$\perp \overline{\mu}_{s,\ell} \geq 0 \qquad \forall s, l \tag{KKT G2}$$

$$0 \leq \sum_{n} H_{\ell,n} v_{s,n} + K_{\ell}$$
$$\perp \underline{\mu}_{s,\ell} \geq 0 \qquad \forall s, l \tag{KKT G3}$$

$$0 = v_{s,n'}$$
$$(\gamma_{s,n}, free) \qquad \forall s, n \tag{KKT G4}$$

$$0 = \sum_{i} r_{s,n,i} - \sum_{i} \sum_{u \in \mathcal{U}_{n,i}} g_{s,n,i,u} - \sum_{i} stout_{s,n,i} + \sum_{i} stin_{s,n,i} + \sum_{nn} B_{n,nn} v_{s,nn}$$
$$(\omega_{s,n}, free) \qquad \forall s, n \tag{MC 1}$$

$$0 \leq \sum_{i} r_{s,n,i} + G^{wind}_{s,n} + G^{solar}_{s,n}$$
$$(\alpha_{s,n} \geq 0) \qquad \forall s, n \tag{MC 2}$$

# Chapter 4

# Numerical applications

## 4.1 Model application

Both the social welfare maximization model of perfect competition (PC) and the Cournot oligopoly model (CO) are implemented in GAMS (General Algebraic Modeling System) software as mixed complementarity problems (MCP). In order to gain insights about the models and their market impacts, a numerical analysis with a test network will be performed. This is done with a fifteen-node network representing a simplified Western European power grid, which is based on Neuhoff et al. [2005], and which has been used for instance by Gabriel and Leuthold [2010]. An illustration is presented in Figure 4.1. The grid's nodes represent Germany (n1), France (n2), Belgium (n3, n6) and the Netherlands (n4, n5, n7). Eight auxiliary nodes (n8 - n15) have no supply or demand, which are included for modeling purposes to account for cross-border flows. The model is solved with the PATH solver, which is a generalization of Newton's method for finding an optimal solution numerically [Ferris and Munson, 2000].

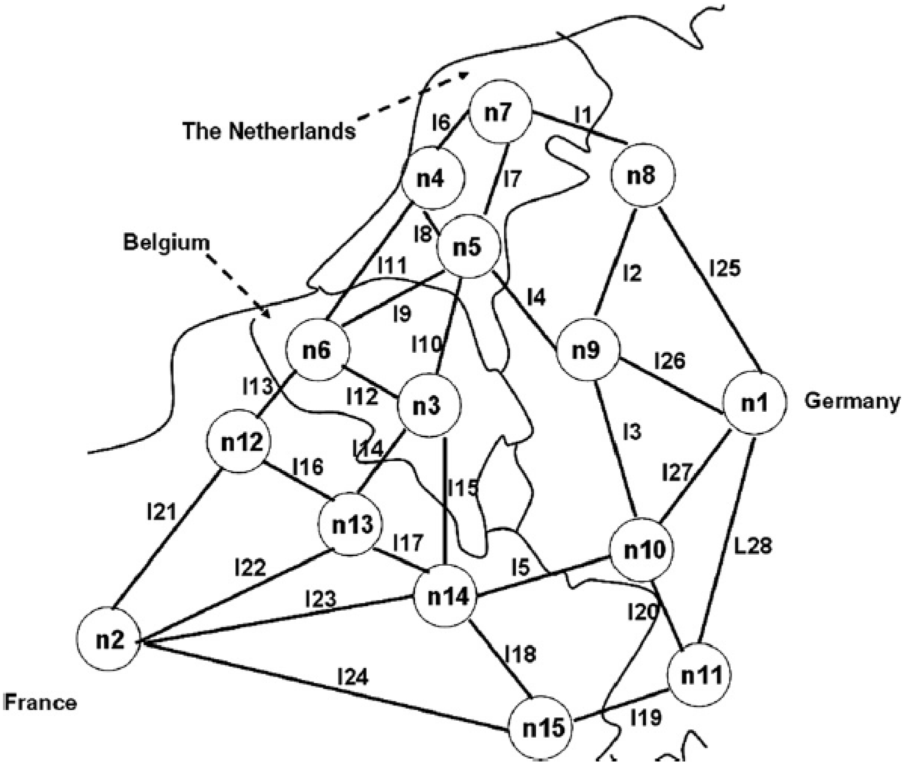


Figure 4.1: An illustration of the fifteen-node network. Source: [Gabriel and Leuthold, 2010]. Based on: [Neuhoff et al., 2005].

### 4.1.1 Description of data

In spite of the usefulness and relevance of numerical modeling in electricity markets, there is not much publicly available and transparent high-quality data. This concerns both networks as well as market data such as costs and is often justified by system security and economic sensitivity reasons. However, there have been improvements during the past few years. There have also been changes in regulation, which is requiring transmission system operators (TSOs) to provide transparent up-to-date data [Egerer et al., 2014].

For the purposes of this thesis, aggregated data can be used to gain insights as long as they are validated and are consistent with observed market outcomes. The data in this section have been gathered from various sources for years 2011 - 2012, using the data documentation by Deutsches Institut für Wirtschaftsforschung (The German Institute for Economic Research) [Egerer et al., 2014] as a starting point. An exception is the installed storage capacity, which reflects current data from 2014. Data validation has been done by a model calibration exercise so that similar electricity prices and generation mix were observed as historic data on nodal levels. The following data are also in line with main references, which are separately mentioned in the corresponding sections.

### Network

The grid parameters for the network in Figure 4.1 in Table 4.1 are based on the model by Gabriel and Leuthold [2010]. Maximum line capacities, in particular, play a significant role in network operations. Lines' thermal characteristics can cause congestion, which requires flow monitoring and indirect control of flows in generation.

Table 4.1: Grid parameters of the fifteen-node network.

| **Line** | **Maximum capacity (MW)** | **Reactance (Ω)** |
|---|---|---|
| line1 | 2971 | 12 |
| line2 | 1842 | 69 |
| line3 | 1842 | 43 |
| line4 | 896 | 28 |
| line5 | 1326 | 25 |
| line6 | 1842 | 33 |
| line7 | 1842 | 50 |
| line8 | 1842 | 29 |
| line9 | 641 | 61 |
| line10 | 641 | 42 |
| line11 | 936 | 34 |
| line12 | 1842 | 31 |
| line13 | 898 | 55 |
| line14 | 1207 | 45 |
| line15 | 267 | 156 |
| line16 | 2762 | 22 |
| line17 | 1842 | 27 |
| line18 | 3329 | 38 |
| line19 | 1282 | 11 |
| line20 | 3329 | 41 |
| line21 | 20000 | 46 |
| line22 | 20000 | 46 |

| | | |
|---|---|---|
| line23 | 20000 | 46 |
| line24 | 20000 | 46 |
| line25 | 20000 | 46 |
| line26 | 20000 | 46 |
| line27 | 20000 | 46 |
| line28 | 20000 | 46 |

### Demand

In order to use the linear inverse demand function (3.7), parameters $D_{s,n}^{int}$ and $D_{s,n}^{slp}$ must be defined. They can be calculated from nodal reference demand and nodal reference price, which are an annual average hourly load and average spot price (for details, see [Florian U. Leuthold, 2010]). These are listed for each node in Table 4.2 as presented by Egerer et al. [2014]. Reference demand for Belgium is divided between n3 and n6 in ratio 20% - 80%, respectively. These represent nodes' relative shares of country's total demand, i.e. the demand in n3 is assumed to be 20 % of Belgium's total demand. Similarly, reference demand in the Netherlands is divided between n4, n5, and n7 approximately in ratio 60% - 20% - 20%, respectively.

Table 4.2: Reference demand and reference price for each node.

| **Node** | **Reference demand (GW)** | **Reference price (€/MWh)** |
|---|---|---|
| n1 | 62 | 51 |
| n2 | 55 | 49 |
| n3 | 2 | 49 |
| n4 | 8 | 52 |
| n5 | 3 | 52 |
| n6 | 8 | 49 |
| n7 | 3 | 52 |

Furthermore, a price elasticity of demand at the reference point must be assumed. Electricity demand on the short-term is relatively inelastic because its retail price fluctuations are usually not directly reported to the end customers in real time [Stoft, 2002]. According to a review by Fan and Hyndman [2011] the price elasticity of electricity demand is usually between -0.1 and -0.4. Thus, the value -0.25 which has also been used by Egerer et al. [2014] is chosen for the baseline case.

Regarding scenarios and the corresponding time periods, the following load profile in Table 4.3 as presented by Daniel Huppmann and Friedrich Kunz [2011] and based on ENTSO-E [n.d.] will be used. The load profile represents how the average demand increases with time, when a value of one represents the hourly average demand. In other words, the studied time frame can be interpreted as a four-hour morning interval, in which electricity demand increases by each hour until it reaches a typical demand. In order to achieve a realistic starting point for the numerical analysis, the ramp up constraint (3.11c) does not apply in the first period $t5$.

Table 4.3: Load profile for each time period.

| **Time** | **Load factor** |
|---|---|
| t5 | 0.84 |
| t6 | 0.92 |
| t7 | 1.01 |
| t8 | 1.07 |

### Marginal and ramping costs

Generation costs by technology type and their corresponding ramp up costs are listed in Table 4.4. Marginal production costs are based on Gabriel and Leuthold [2010], and they reflect fuel and carbon emissions. They can be used because the merit-order curve, which ranks energy sources in ascending order by their production costs, has been observed to remain very similar over the past decade [Egerer et al., 2014].

Furthermore, in order to balance supply and demand, electricity generation must be ramped up and down from time to time. The complexity of generation processes causes technology-specific costs when the output is adjusted (known as ramping costs). These are related to the decreased fuel efficiency compared to constant generation as well as increased stress on generators' components and, thus, "fatigue damage" and replacement costs [Werner, 2014].

Generation types with the lowest marginal costs and high ramp-up costs generally provide the baseline generation. When demand increases, more generation is being dispatched according to the merit-order curve. There are notable differences in the costs, risks, and flexibility related to ramping up a specific technology, which makes it infeasible to use some technologies for rapid increase in generation.

Consequently, nuclear generators usually provide constant baseline supply, while natural gas is cheap and flexible to follow the intraday demand [Werner, 2014]. Ramping costs, too, vary significantly with the generation schedule, operation constraints, plant design, size, and age, as well as the ramping rate, which makes them difficult to estimate precisely [Kumar et al., 2012]. For the purposes of our analysis, approximate costs based on a DIW model as presented by Daniel Huppmann and Friedrich Kunz [2011] will be used. These costs are roughly in line and ranked according to their feasibility as presented by Werner [2014]; Kumar et al. [2012]; Wang and Shahidehpour [1995]. In other words, the primary option for ramping is flexible production such as gas, oil, and coal plants, as can be seen from Table 4.4. Nuclear plants, on the other hand, serve for the base load. Hydro plants do not have fuel or marginal costs, which is why their costs are linked to ramping.

Table 4.4: Marginal costs and ramp-up costs for conventional generation.

| **Type** | **Marginal Cost (€/MWh)** | **Ramp-up Cost (€/MWh)** |
|---|---|---|
| **u1 (Nuclear)** | 10 | 6.7 |
| **u2 (Lignite)** | 20 | 6.7 |
| **u3 (Coal)** | 22 | 4.7 |
| **u4 (CCGT)** | 30 | 5.8 |
| **u5 (Gas)** | 45 | 2.3 |
| **u6 (Oil)** | 60 | 2.3 |
| **u7 (Hydro)** | 0 | 6.7 |

### Installed generation capacity

The approximations of installed production capacities at each node are listed in Table 4.5 as by Egerer et al. [2014]. Generation types u1-u7 represent conventional generation as explained in the preceding Table 4.4. Columns "Wind" and "Solar" represent installed capacity for renewable generation, but the realized generation is handled as external parameters according to the scenario tree in Figure 3.2. Furthermore, due to insufficient information, the capacity for Belgium and Netherlands is divided between the corresponding nodes relative to demand, not by realistic location. However, the approximation as a whole appears sufficient for overall analysis of the network.

To model decisions in a Cournot oligopoly, corresponding data on a company level must be estimated. The firm-specific figures for years 2011-2012 in

Table 4.6 were gathered from their Websites and annual activity reports. Companies with the largest national shares of electricity production were taken into account. The total capacities are the same as in Table 4.5, so all the remaining capacity for each country is allocated to a group called "Fringe." As the distinction between generation types u4 (CCGT) and u5 (gas) was not reported in most cases, these capacities have been estimated based on firm level totals for u4 and u5 combined, and node-level totals from Table 4.5.

Table 4.5: Installed capacity for electricity generation in GW.

| **Node/Type** | **u1** | **u2** | **u3** | **u4** | **u5** | **u6** | **u7** | **Wind** | **Solar** |
|---|---|---|---|---|---|---|---|---|---|
| **n1** | 12 | 20 | 25 | 11 | 10 | 4 | 2 | 29 | 25 |
| **n2** | 63 | 2 | 4 | 3 | 2 | 7 | 17 | 7 | 3 |
| **n3** | 1 | - | - | 1 | - | - | - | - | - |
| **n4** | - | - | 2 | 6 | 3 | - | - | 1 | - |
| **n5** | - | - | 1 | 2 | 1 | - | - | - | - |
| **n6** | 5 | - | 1 | 3 | 1 | - | - | 1 | 2 |
| **n7** | - | - | 1 | 2 | 1 | - | - | 1 | - |

Table 4.6: Installed capacity of electricity generation for companies in GW.

| **Nodes** | **Company/Type** | **u1** | **u2** | **u3** | **u4** | **u5** | **u6** | **u7** |
|---|---|---|---|---|---|---|---|---|
| **n1** | **E.ON** | 5 | 1 | 5 | 2 | 2 | 1 | - |
| | **RWE** | 4 | 10 | 5 | 3 | 3 | - | 0.5 |
| | **EnBW** | 3 | - | 4 | 0.5 | - | 0.5 | 0.5 |
| | **Vattenfall** | - | 9 | 2 | 1 | 1 | 0.5 | - |
| | **FringeD** | - | - | 9 | 4.5 | 4 | 2 | 1 |
| **n2** | **EDF** | 63 | - | 4 | - | - | 7 | 15 |
| | **FringeF** | - | 2 | - | 3 | 2 | - | 2 |
| **n3,n6** | **Electrabel GDF Suez** | 4 | - | - | 3 | 1 | - | - |
| | **FringeB** | 2 | - | 1 | 1 | - | - | - |
| **n4,n5,n7** | **GDF Suez** | - | - | 1 | 3 | 2 | - | - |
| | **Essent** | - | - | 1 | 1.5 | - | - | - |
| | **N.V. Nuon Energy** | - | - | 1 | 2 | 1 | - | - |
| | **FringeN** | - | - | 1 | 3.5 | 2 | - | - |

The data of Table 4.6 is approximate and stylized, but its main purpose is to serve as a starting point to see what happens when market power is present. Again, the data for Belgium's and the Netherlands' nodes are allocated according to their respective demand. All in all, due to the stylized form of the data, it is not possible to perform in-depth firm-level analyses, but it is suitable for analyzing aggregate market outcomes.

In order to account for the time when plants are offline, such as for outages and revisions, only a defined share of the total installed capacity for each production type is assumed to be available for generation. These availabilities are listed in Table 4.7 based on Egerer et al. [2014]. Whenever an availability range was provided, an average number is being used. These are also in line with Schill and Kemfert [2011], in which an average availability of 80% was used for each generation type.

Table 4.7: Average availability percentage of the total installed capacity by generation type.

| **Type** | **Availability** |
|---|---|
| **u1 (Nuclear)** | 80% |
| **u2 (Lignite)** | 85% |
| **u3 (Coal)** | 84% |
| **u4 (CCGT)** | 89% |
| **u5 (Gas)** | 86% |
| **u6 (Oil)** | 86% |
| **u7 (Hydro)** | 30% |

### Electricity storage

Due to a lack of reliable data, storage operating costs are assumed to be zero as done by Schill and Kemfert [2011], for example. This leads to slightly optimistic arbitrage for producers, but it is still close to reality as the costs may be rather low. Although the costs per storage technology may vary, considering that most of the current capacity is PHS, this can be considered to be a decent assumption due to the practically non-existing marginal costs of hydropower operation (please refer to Table 4.4).

Installed capacities for electricity storage are presented in Table 4.8. Data for power (GW) are based on current installations according to Sandia National Laboratories [2014]. All projects under construction, announced, and contracted projects as well as installations that are offline have been excluded. Power is converted to energy (GWh) according to the given operational durations for Germany and Belgium. For France these data are missing, and the respective energy is estimated based on the data for Germany's pumped hydro storage assuming that a 1 GW plant can operate at that rate on average for 5 hours.

In Belgium and France effectively 100% and in Germany nearly 90% of the installed storage capacity is pumped hydro technology. In the Netherlands, there does not exist any significant grid-connected electricity storage capacity, only minor electrochemical installations [Sandia National Laboratories, 2014]. Capacities in Table 4.8 are well in line with the pumped hydro capacities listed by Egerer et al. [2014] and with the installed storage capacity for Germany as presented by Schill and Kemfert [2011].

Table 4.8: Storage capacities for each node in GW and GWh. Based on Sandia National Laboratories [2014].

| **Node** | **Capacity, power (GW)** | **Capacity, energy (GWh)** |
|---|---|---|
| n1 | 7 | 36 |
| n2 | 6 | 30 |
| n3 | 0.3 | 1 |
| n4 | 0 | 0 |
| n5 | 0 | 0 |
| n6 | 1 | 5 |
| n7 | 0 | 0 |

Storage capacities for the companies have been estimated based on operational storage projects in 2014 as reported by Sandia National Laboratories [2014] and are presented in Table 4.9. There is no operating grid-scale storage capacity in the Netherlands, and the allocation of capacity for Belgium's nodes has again been estimated relative to the node demand.

Table 4.9: Storage capacity estimations for companies in GWh. Based on Sandia National Laboratories [2014].

| **Node** | **Company** | **Capacity, energy (GWh)** |
|---|---|---|
| n1 | E.ON | 5 |
| n1 | RWE | 11 |
| n1 | EnBW | 1 |
| n1 | Vattenfall | 16 |
| n1 | FringeD | 3 |
| n2 | EDF | 30 |
| n3,n6 | Electrabel GDF Suez | 6 |

Other parameter values related to storage are listed in Table 4.10. $EI$, $RI$, and *RO* are based on Schill and Kemfert [2011]. It should be noted that efficiency is much dependent on the storage technology, and these figures represent one, presumably average case. It is also assumed that on a short time scale, no losses are made for the stored electricity, i.e., $ES = 1$.

Table 4.10: Other parameters related to storage.

| **Parameter** | **Description** | **Value** |
|---|---|---|
| ES | Periodic storage efficiency | 1 |
| EI | Storage input efficiency | 0.75 |
| RI | Rate at which storage can be charged | 0.16 |
| RO | Rate at which storage can be discharged | 0.16 |

### 4.1.2 Case presentation

The numerical analyses will be performed for the four different cases in Table 4.11. That is, the results will be examined for both models with and without storage capacity. Additionally, sensitivity analyses regarding parameter assumptions for uncertainty in renewable production's scenario tree and price elasticity of demand will be conducted.

Table 4.11: Test cases for the numerical analysis.

| **Test case** | **Model** | **Storage** |
|---|---|---|
| Case 1 - PC-ns | PC | No storage |
| Case 2 - PC-s | PC | Storage |
| Case 3 - CO-ns | CO | No storage |
| Case 4 - CO-s | CO | Storage |

## 4.2 Results

Table 4.12 summarizes computational statistics for using PATH solver for the fifteen-node network. Statistics include our four test cases from Table 4.11 with their default parameters. The model was run with a personal computer, which has 8,00 GB RAM and processor Intel(R) Core(TM) i5-3427U CPU @ 1.80 GHz. It can be seen that including storage in the model increases computation time significantly, especially in the Cournot oligopoly. However, when there is no storage capacity in the grid, computation times do not significantly differ between the two models. Nevertheless, the number of single equations and variables is substantially larger in the Cournot oligopoly model than in perfect competition.

Table 4.12: GAMS Model Statistics for the fifteen-node network, solver PATH. Cases 1-4 of the numerical analysis.

| **Test case** | **Equations** | **Variables** | **Time** |
|---|---:|---:|---:|
| Case 1 - PC-ns | 10,065 | 10,185 | 5.3 s |
| Case 2 - PC-s | 10,065 | 10,185 | 11.7 s |
| Case 3 - CO-ns | 107,010 | 108,450 | 3.6 s |
| Case 4 - CO-s | 107,010 | 108,450 | 86.8 s |

### 4.2.1 Market price

The expected prices across all scenarios $s$ for each hour $t$ are presented in Figure 4.2 for the cases 1-4. The price-smoothing effect of storage is clearly visible because the price curve becomes flatter in cases 2 (PC-s) and 4 (CO-s) when comparing to 1 (PC-ns) and 3 (CO-ns), respectively. This is due to excess electricity being moved from off-peak ($t5$ and $t6$) to peak demand ($t7$ and $t8$) periods when its relative shortage otherwise would cause market prices to increase. Moving energy with storage now increases (decreases) supply and decreases (increases) prices during peak (off-peak) periods.

In the case of perfect competition, this can be interpreted as an action of a welfare-maximizing central planner, who moves energy to those time periods when it is valued the most by the whole market, i.e., when it maximizes social welfare. On the other hand, in Cournot oligopoly, storage is operated and energy is moved by power companies, which try to maximize their own profit knowing that they can affect the price while being at the mercy of other similarly acting companies. Based on Figure 4.2, the price-smoothing effect seems to be roughly similar during off-peak hours for both models. However, during peak hours it is relatively diminished in Cournot oligopoly when comparing to perfect competition. In other words, by holding back their supply during peak hours producers in Cournot oligopoly are able to diminish the price decrease, which is beneficial for them.

When comparing perfect competition (cases 1-2) to Cournot oligopoly (cases 3-4), it can be seen that in the presence of market power prices are at all points above competitive prices. However, at the last studied hour $t8$ the price of electricity in case 4 (CO-s) approaches the price in case 1 (PC-ns). This would indicate that during peak hours storage diminishes the extent to which strategic producers are able to obtain higher prices than economically would be efficient without storage. However, without storage (case 1 vs. case 3) prices are 39-15% higher in CO than in PC, with a decreasing trend towards peak hours. With storage (case 2 vs. case 4) the range is narrower, 35-23%, indicating that storage benefits producers more in CO than in PC during peak hours, but, on the contrary, less during off-peak hours.

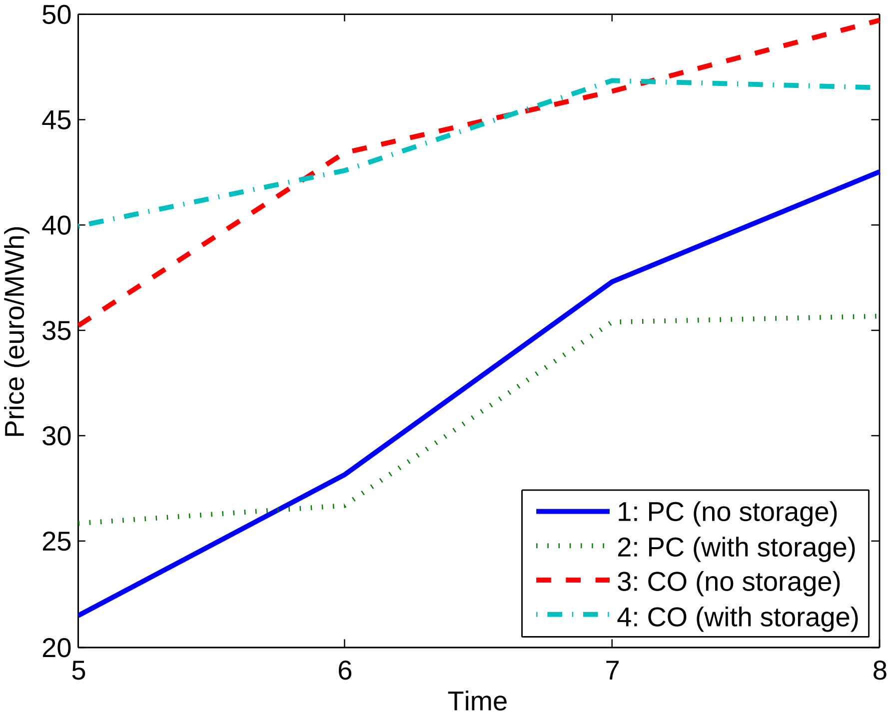


Figure 4.2: Expected prices in cases 1-4.

### 4.2.2 Production mix and generation costs

In terms of generation mix, electricity is being produced by different types of units according to the merit-order curve, i.e., by using the cheapest available plants up to their available capacity until the equilibrium demand quantity is reached. For the setup and assumptions of this thesis, in an optimal solution for cases 1 and 3, oil ($u6$) and gas ($u5$) plants because of their high operating costs do not need to be in operation. The possibility to use storage has an effect on the generation mix in cases 2 (PC-s) and 4 (CO-s). In general, producers generate more electricity during off-peak periods in order to store it, although there is less electricity supply in the market.

In addition, when producers are able to store electricity, they do not need to rely only on ramping up their generation when demand increases towards the high-peak periods. This brings savings in ramp-up costs. Cost-savings due to having storage are presented in Figure 4.3. In both market circumstances, producers save substantially on ramp-up costs when they have storage capacity. The effect is clearly larger in perfect competition (-85%) but also significant in Cournot oligopoly (-57%).

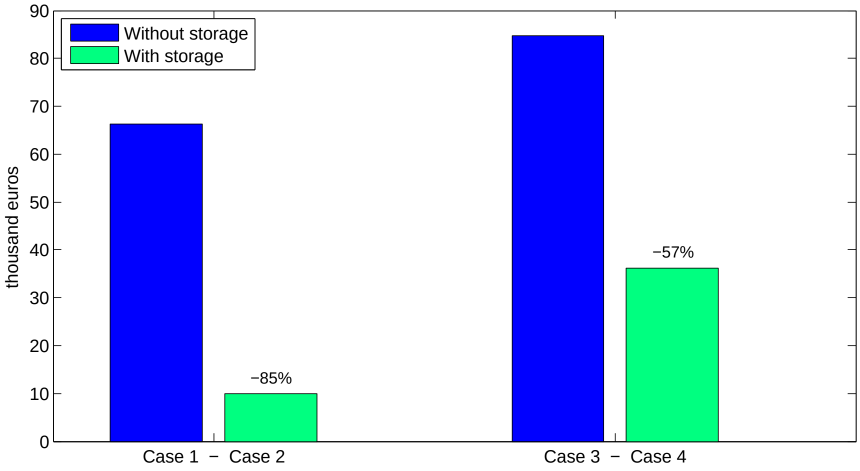


Figure 4.3: Expected ramp-up costs for cases 1-4.

### 4.2.3 Market power and storage operations

The optimal values for storage variables in cases 2 (PC-s) and 4 (CO-s) are in Figure 4.4. It is optimal to charge storage during off-peak periods and move electricity to be discharged during peak periods when market prices are higher due to the increased demand. When comparing the two market settings, storage is less used in Cournot oligopoly than in perfect competition. This is a result of strategic decisions of Cournot companies because this way they are able to keep the supply level lower and, thus, drive prices higher than what would be effective in economic terms. In this numerical example, hourly storage levels in Cournot competition are 18-32% less than in perfect competition. In addition, storage operations in CO are relatively faster than in PC in such a way that almost all charge and discharge happens at $t5$ and $t8$, while in PC operations are more evenly divided between the hours, especially for storage discharge *stout*. Specifically, the storage efficiency defined by parameter $EI$ causes variables *st* and *stout* to be 75% of the corresponding *stin*.

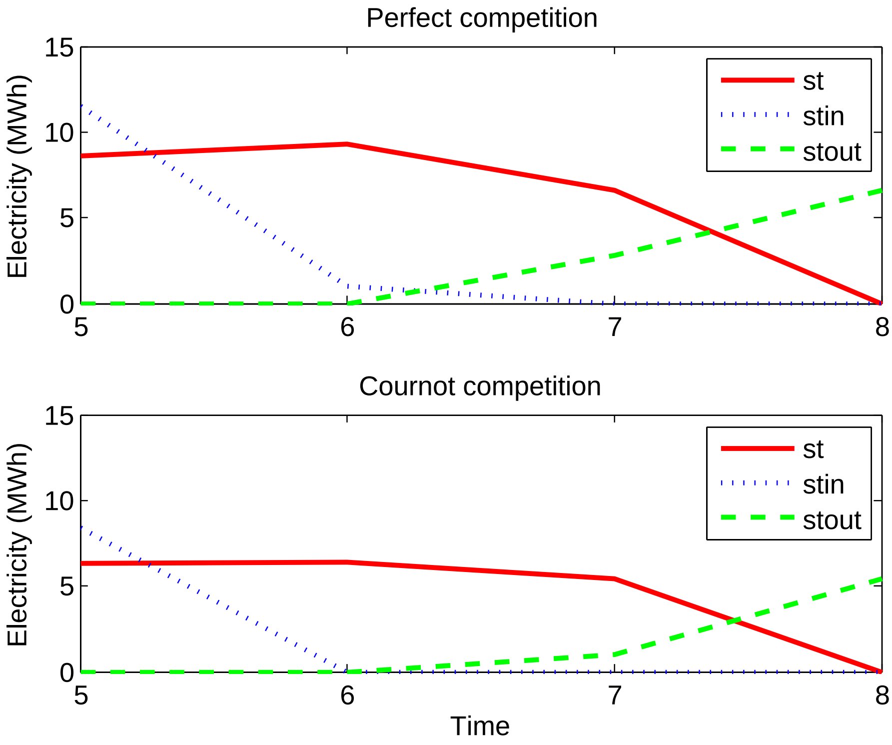


Figure 4.4: Storage use in perfect competition versus Cournot competition.

### 4.2.4 Welfare effects

The expected values for social welfare (SW), consumer surplus (CS), and producer surplus (PS) in cases 1-4 are presented in Table 4.13, and the respective effects of storage for these measures in perfect competition compared to Cournot oligopoly are illustrated in Figure 4.5.

Table 4.13: Expected welfare measures PS, CS, and SW in cases 1-4 (k€).

| **Test case** | **PS** | **CS** | **SW** |
|---|---|---|---|
| Case 1 | 10 102 | 65 416 | 75 518 |
| Case 2 | 9 160 | 66 427 | 75 587 |
| Case 3 | 16 231 | 59 021 | 75 251 |
| Case 4 | 16 281 | 59 008 | 75 290 |

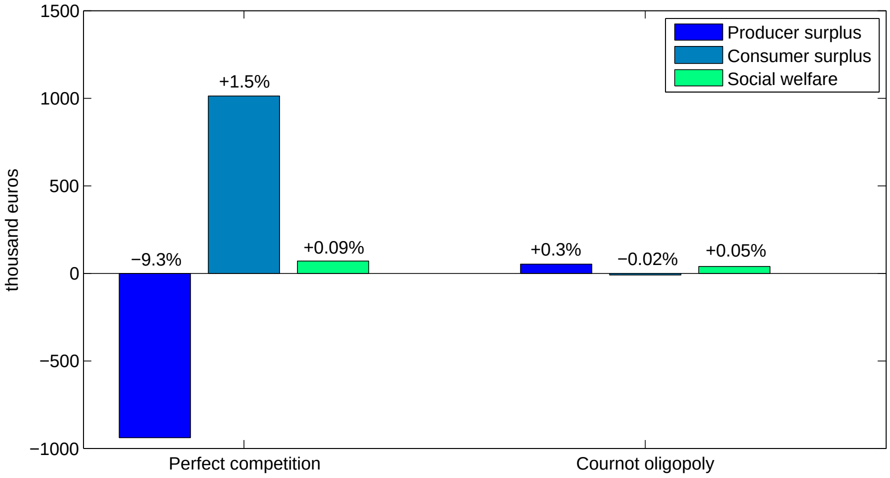


Figure 4.5: Storage's effect on the expected values of welfare measures: a change from the grid with no storage to the grid with storage.

In general, the results suggest that storage increases social welfare in both market settings. The effect is, nevertheless, slightly reduced in the case of Cournot oligopoly, as the increase of SW in CO is almost half of what it is in PC. In economic terms, imperfect competition also reduces market efficiency, which can be seen in Table 4.13 as reduced SW in cases 3 (CO-ns) and 4 (CO-s) compared to 1 (PC-ns) and 2 (PC-s), respectively.

In perfect competition, storage also increases consumer surplus, while it reduces producer surplus. Relatively, the decrease in PS (-9.3%) is also much larger than the increase in CS (+1.5%). The change in surpluses is a result of the linear demand curve and price-smoothing across time periods: in the studied model, the electricity price decreases at peak demand more in relative terms than it increases at low demand, which benefits consumers. Consequently, although producers avoid ramping costs and production constraints when they can use storage, the decreased price at peak demand outweighs their effect.

However, in the case of Cournot oligopoly the situation of market participants turns upside down. Now, producers are able to benefit from the presence of storage (+0.3%) at the expense of consumers, although to a much smaller extent than consumers benefit in perfect competition. As a matter of fact, the relative decrease in consumer surplus (-0.02%) is rather insignificant. Again, the results can be explained by the price-smoothing effect, which is illustrated in Figure 4.2. This is because the increase in producers' off-peak revenue more than compensates for the decrease in high-peak revenue.

First, this is a result of the relative changes in prices as a result of storage. In PC the price decrease at $t8$ is -6.81 €/MWh and the increase at $t5$ is +4.35 €/MWh. Furthermore, when more electricity is sold at $t8$, the effect of storage for producers is clearly undesirable. In CO, however, the price change at $t8$ is -3.23 €/MWh and at $t5$ +4.72 €/MWh, mainly due to the strategically lowered supply at peak-demand. The shift is just enough to compensate for the difference in sales between off-peak and peak demand, and, thus, it benefits producers.

Second, although producers are not able to benefit from their ramp-up savings (see Figure 4.3) in perfect competition, this for its part contributes to the increase in PS in Cournot oligopoly. In other words, companies with storage capacity are better off when they have some control over the market price because it seems that then they are able to make use of storage to their own benefit. All in all, society benefits from storage regardless of which market participant is the real gainer.

### 4.2.5 Network congestion

To measure how storage can alleviate network congestion, an expected grid owner's profit from electricity transmission as defined in equation (3.15) will be observed. For perfect competition's social welfare maximization model, the transmission cost $\omega$ is obtained from an equivalent formulation of profit-maximizing companies. The differences are reported in Figure 4.6.

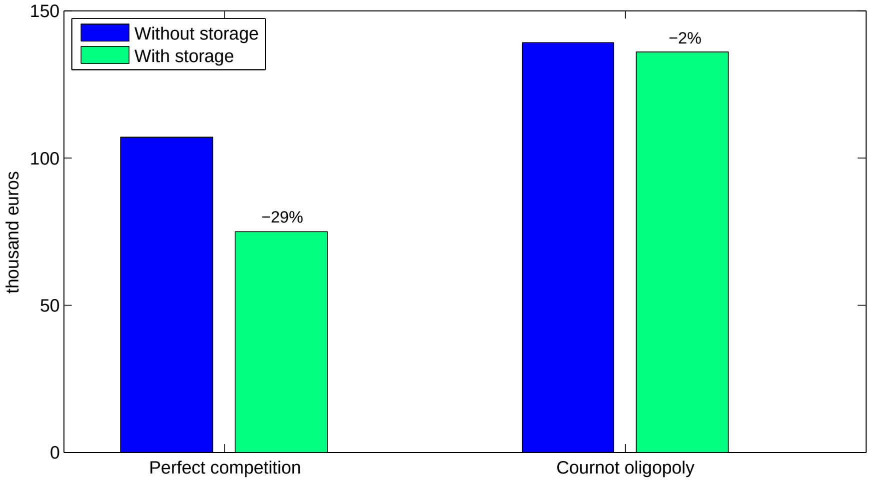


Figure 4.6: The impact of storage on network congestion as measured by grid owner's profit.

As a result, it can be stated that storage capacity in the grid alleviates network's congestion if measured by the grid owner's profit. The difference seems to be much larger in the case of perfect competition: accumulated transmission costs decrease by 29% for the studied network. In Cournot oligopoly, the transmission costs altogether are much larger. However, the alleviating effect of storage is much smaller, only 2%, although observable. In general, the fact that there is more network congestion in CO is most likely a result of strategically decreased supply in some nodes, which increases the need to increase electricity transmission. Thus, the extra capacity of storage is not enough to compensate if it is not used to full extent.

### 4.2.6 Sensitivity analysis

**Elasticity**

To test the how sensitive the results are to the choice of elasticity parameter, the perfect competition model is run when the price elasticity at reference point is decreased to -0.20 and when it is increased to -0.30. Due to computational reasons, a similar analysis is performed for the Cournot oligopoly model when elasticity range is a bit narrower, at -0.21 and at -0.30. The results are in Tables 4.14 and 4.15.

The choice of price elasticity parameter has a direct influence on the parameters of linear inverse demand function, $D_{s,n}^{int}$ and $D_{s,n}^{slp}$, i.e., the intersection point and the slope of the curve. Increasing elasticity decreases the parameters and vice versa. The situation is illustrated in Figure 4.7. For more details, please refer to [Florian U. Leuthold, 2010]. Thus, the reclining demand curve (from demand to demand') causes SW and CS to decrease as they decline in area when elasticity is increased. Additionally, changing elasticity also has an effect on the equilibrium price. In case the price is above (below) the reference equilibrium price of the previous curve, demand, PS will increase (decrease).

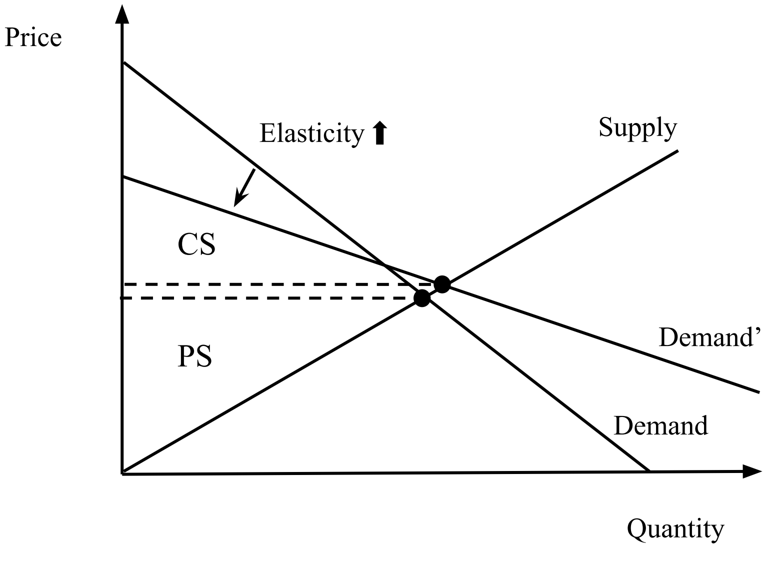


Figure 4.7: Changes in the demand curve and equilibrium price when elasticity is increased.

Table 4.14: Expected welfare measures for perfect competition when elasticity increases, (k€).

| | | **No Storage** | | **Storage** | | **Δ from storage** | |
|---|---|---|---|---|---|---|---|
| $\epsilon$ | | Value | $\epsilon$-change | Value | $\epsilon$-change | Value | $\epsilon$-change |
| -0.20 | PS | 9 130 | - | 8 637 | - | -493 | -5.4% |
| | CS | 80 080 | - | 80 641 | - | +561 | +0.7% |
| | SW | 89 210 | - | 89 278 | - | +68 | +0.1% |
| -0.25 | PS | 10 102 | +11% | 9 160 | +6% | -942 | -9.3% |
| | CS | 65 416 | -18% | 66 427 | -18% | +1 012 | +1.5% |
| | SW | 75 517 | -15% | 75 587 | -15% | +70 | +0.1% |
| -0.30 | PS | 10 838 | +7% | 10 503 | +15% | -335 | -3.1% |
| | CS | 55 574 | -15% | 55 981 | -16% | +407 | +0.7% |
| | SW | 66 412 | -12% | 66 484 | -12% | +72 | +0.1% |

Table 4.15: Expected welfare measures for Cournot oligopoly when elasticity increases, (k€).

| | | **No Storage** | | **Storage** | | **Δ from storage** | |
|---|---|---|---|---|---|---|---|
| $\epsilon$ | | Value | $\epsilon$-change | Value | $\epsilon$-change | Value | $\epsilon$-change |
| -0.21 | PS | 17 145 | - | 17 261 | - | 117 | +0.7% |
| | CS | 68 481 | - | 68 404 | - | -78 | -0.1% |
| | SW | 85 626 | - | 85 665 | - | +39 | +0.1% |
| -0.25 | PS | 16 231 | -5% | 16 281 | -6% | +50 | +0.3% |
| | CS | 59 021 | -14% | 59 008 | -14% | -13 | 0.0% |
| | SW | 75 252 | -12% | 75 290 | -12% | +38 | +0.1% |
| -0.30 | PS | 15 478 | -5% | 15 326 | -6% | -152 | -1.0% |
| | CS | 50 725 | -14% | 50 933 | -14% | +208 | +0.4% |
| | SW | 66 203 | -12% | 66 259 | -12% | +56 | +0.1% |

In the studied network, increasing the absolute value of price elasticity at reference point leads to a higher equilibrium price and increased PS in perfect competition (Table 4.14), which is the case illustrated in Figure 4.7. Respectively, increasing price elasticity yields lower equilibrium price and decreased PS in Cournot oligopoly (Table 4.15). This is due to the relatively larger increase in total demand as a result of elasticity-increase, which occurs in CO in comparison to PC. Thus, with higher price elasticity producers' control over the market is in a way diminished. As a result, in CO the equilibrium demand exceeds the point at which elasticity increase leads to higher price.

When it comes to storage's effect on social welfare, there seems to be no significant difference neither between elasticity choices nor between the models: the benefit for social welfare is always of magnitude 0.1%. However, there is more variation in how storage affects PS and CS in perfect competition. A potential explanation is that in the Cournot case, producers are able to have a bigger influence on their profit, which evens out the distribution of welfare between consumers and producers.

It is, however, difficult to draw conclusions on why the negative effect of storage for producers in perfect competition is diminished both with elasticity increase and with elasticity decrease. Most likely this is an intricate result of how the market equilibrium settles in each case. In fact, the more inelastic demand is, the more one could assume producers to benefit. Thus, it is possible that some elasticity values, such as -0.30 in this analysis, are already out of a realistic scope for the PC model. All in all, the overall effects in PC are similar across all tested elasticities.

In addition, although producers were observed to benefit from storage in Cournot oligopoly when price elasticity is -0.25 (Figure 4.5), the situation seems to change when price elasticity is at -0.30. Then, consumers benefit from storage and producers' profit is hurt. However, when price elasticity is at 0.21, producers' benefit is in fact a little bit strengthened. Thus, the outcome of the Cournot oligopoly model is more sensitive to the choice of elasticity parameter and a threshold, at which the surplus distribution between the market participants changes, can be observed.

### Uncertainty

One of the main incentives to install storage capacity into the grid is to integrate intermittent renewable energy. Thus, it is justified to study how changes in the volatility of renewable energy generation would affect the results. This is carried out by analyzing the results for PC model when the standard deviation of wind energy generation in the scenario tree of Figure 3.2 is increased from 0.06 to 0.15. The expected wind generation remains the same across all scenarios. Another analysis is performed for a deterministic case of reduced volatility, in which generation for each scenario $s$ is the corresponding expected generation of the time period $t$ in question. This is denoted as the case when standard deviation is decreased to 0.01. Solar generation's uncertainty is not considered because the available capacity is relatively easier to forecast. Additionally, the results for the Cournot oligopoly are left from the analysis due to computational reasons.

The results for perfect competition model are presented in Table 4.16. There seems to be no significant changes in storage's impact on social welfare when the volatility of wind generation changes. However, the effect of storage, albeit small, is always beneficial for the society in economic terms. In addition, the larger the standard deviation, the smaller the gap between the effect of storage for producers and consumers gets. In other words, when the uncertainties are greater, the more equitable the distribution of surpluses as a result of storage is. This is because producers are able to use their storage capacity more in the presence of uncertainties.

Table 4.16: Expected welfare measures for perfect competition when standard deviation of wind generation production increases, (k€).

| | | **No Storage** | | **Storage** | | **Δ from storage** | |
|---|---|---|---|---|---|---|---|
| $\sigma$ | | Value | $\sigma$-change | Value | $\sigma$-change | Value | $\sigma$-change |
| 0.01 | PS | 10 121 | - | 9 095 | - | -1 026 | -10.1% |
| | CS | 65 397 | - | 66 494 | - | +1 096 | +1.7% |
| | SW | 75 519 | - | 75 588 | - | +70 | +0.1% |
| 0.06 | PS | 10 102 | -0.2% | 9 160 | +0.7% | -942 | -9.3% |
| | CS | 65 416 | 0.0% | 66 427 | -0.1% | +1 012 | +1.5% |
| | SW | 75 517 | 0.0% | 75 587 | 0.0% | +70 | +0.1% |
| 0.15 | PS | 10 103 | 0.0% | 9 440 | +3.1% | -663 | -6.6% |
| | CS | 65 388 | 0.0% | 66 127 | -0.5% | +739 | +1.1% |
| | SW | 75 490 | 0.0% | 75 567 | 0.0% | +76 | +0.1% |

## 4.3 Discussion

The assumptions of the model, stylized data for parameters, as well as selection of measures and indicators all have an impact on the conclusions than can be drawn. Thus, the results are primarily indicative and qualitative. To begin with, the assumptions about demand, mainly its linearity, are likely to have one of the most major effects on the results. Linear demand has often been used in connection with electricity market models, such as by Hobbs [2001]; Gabriel and Leuthold [2010], but not with storage models. Thus, it is a justified and novel approach to use it in this context. The effect on price-smoothing is well in line with the intuition of how storage works. However, it is possible that using a different kind of demand curve could lead to rather different results regarding market players' benefits, as was proven when the two models were compared.

We have also studied a relatively short time frame. The four-hour interval provides a convenient representation of dynamic generation and ramp-up decisions, increase in demand, renewable generation's uncertainty, and, consequently, storage's effects, but it does not give an entirely realistic view of storage operations. This is a deliberate choice specifically to restrict the number of scenarios in the scenario tree of Figure 3.2 for computational purposes. Hence, there is no stored electricity at the beginning of modeling, and an optimal strategy is to use all of the remaining stored electricity at the last studied time step because decision makers are not assumed to look things any further than that. Additionally, due to the assumed efficiency restrictions on storage loading and discharging, producers are not able to make full use of their capacity in this short a time frame. As a consequence, the results should be interpreted as providing insights into the key changes that take place in this specific situation rather than providing a realistic time series about storage operations.

As for the market power formulation, it seems logical that storage is less in use in Cournot oligopoly so that producers can hold the supply down and obtain higher prices. Also the fact that producers are able to benefit from storage in imperfect competition with small price elasticity seems reasonable. Additionally, the decrease in social welfare and consumer surplus as well as increase in producer surplus compared to PC are in line with Cournot assumptions. Nevertheless, even though the obtained results are logical, computational instability related to PATH solver's algorithm caused case 4 (CO with storage) to be challenging to solve with some parameter choices, resulting in an "other error" message and failing to find an optimal solution. Thus, the CO model was altogether excluded from the sensitivity analysis about uncertainty, and the price elasticity analysis was performed using a somewhat narrower range than that of the perfect competition model.

Furthermore, although oligopoly models are important in gaining insights into the strategic operations of energy markets, they are always rough simplifications. Hence, it cannot be assumed that they would capture all the essential features of imperfect competition that can have significant importance in reality. For example, in addition to profit maximization, there can be environmental or political reasons for companies to utilize storage in a certain manner. Additionally, other phenomena, such as the threat of entry, are not considered in the Cournot approach [Pahle et al., 2013; Bushnell, 2003]. A case in point, hydro facilities are often affected by regional water policy functions like floods, transportation, and municipal water supplies, which can disturb otherwise optimal electric power production. In consequence, hydro operations are rather transparent to public and may complicate some strategic operations, such as “spilling” of water [Bushnell, 2003]. Thus, a strategic company interested in its public image, reliability and environmental issues, could choose to act differently than the conventional strategy of profit-maximization would indicate.

Further limitations stem from the scoping of the model. For instance, one could argue whether or not social welfare is a good measure of social benefit and market efficiency, and producer and consumer surplus may not uncover the entire truth either. As Stoft has highlighted on his Website of economic science, these measures do not consider behavioral aspects, only the rational profit maximization [Steven Stoft, 2014]. This might be problematic considering all the social and political aspects related to energy production. Above all, such models, without any further constraints or conditions, do not consider environmental or national security aspects. In spite of market liberalization, particularly from grid owner’s and policymaker’s perspective, these nevertheless play a major role in electricity markets. Furthermore, especially from producers’ point of view, reputation and customer satisfaction are important measures, too. Although ramp-up costs are considered in the calculation of producer surplus, the increase or decrease of production-related risks as a result of storage might change the circumstances for producers for its part, too.

Storage capacity may take the role of extra capacity in grid’s nodes and, thus, alleviates congestion in power lines. Because network congestion causes prices to increase, it hurts consumers. The fact that lines are less congested with storage possibility is thus in line also with the increased consumer surplus. As for the choice of price elasticity, it is rather difficult to assess a realistic parameter because it depends among other things on the location and the studied time frame. However, the conducted sensitivity analysis shows that chancing price elasticity hardly changes the overall conclusions of storage’s effects, mainly the relative magnitudes of changes for PS and CS, especially in the case of perfect competition. For particularly high elasticity values, the results of CO, however, reversed when it comes to changes in PS and CS. One could also argue that because storage’s arbitrage for producers is likely to be slightly optimistic due to its zero costs, the relatively small increase in PS is rather dependent on this assumption. In addition, the illustration in Figure 4.7 explains the changes and supports the observations of each measure itself with elasticity increase.

Furthermore, it is perhaps somewhat surprising that the benefit of storage for society does not significantly change when the volatility of renewable generation increases. This is possibly a consequence of using realistic wind generation generation (available capacities) in the first place, which leaves only limited flexibility to adjust the volatility. In other words, the bottom line of zero production can be included, but the maximum capacity cannot be reached so that the expected generation also remains the same.

Finally, when comparing the perfect competition results to the model of Schill and Kemfert [2011], it can be said that the inclusion of network, linear demand, and uncertain renewable generation does not in effect change much of the conclusions that they have, although they use an iso-elastic demand function and a higher value for price-elasticity. In brief, storage smooths market prices and benefits society at the expense of producer surplus. However, for the Cournot oligopoly model the results are reversed. Thus, our analysis shows that in imperfect competition the benefit of society can also result from the increased surplus of producers. Schill and Kemfert also observe higher SW in perfect than in imperfect competition, which corresponds to the results of this thesis. However, they observed that with higher price-elasticity, SW in contrary increases with PS, while CS decreases. This is contrary to our results, and is most likely a consequence of their iso-elasticity assumption for the demand. In addition, they concluded that, as a result of storage, conventional generation is smoother due to a reduced number of binding ramping constraints. This is similar to our result that storage diminishes ramping costs.

Considering other electricity storage models, Bushnell [2003] observed increased inefficiencies such as deadweight loss and misallocation of supply to meet the demand in Cournot oligopoly compared to perfect competition. This is similar to our result of decreased storage use and supply in CO. He also noted that, generally, consumer surplus is typically lower in CO markets in comparison with PC markets, which was observed in this thesis, too. However, no direct conclusions on the social welfare effects of storage were made. In addition, in the perfect competition model by Sioshansi et al. [2009], large-scale storage was observed to improve consumer surplus and social welfare, which is in line with Schill and Kemfert [2011] and the results of our PC model.

# Chapter 5

# Conclusions

In this thesis we have studied the market impacts of storage in a transmission constrained electricity system in which there is uncertainty in renewable generation and inverse demand function (price) is assumed to be a linear function of demand. Based on previously made studies on electricity storage, but with varying approaches and assumptions, the following four hypotheses were set:

> **Hypothesis 1.1**: *Storage increases social welfare and consumer surplus at the expense of producer surplus.*
>
> **Hypothesis 1.2**: *Storage alleviates congestion in a transmission-constrained power system.*
>
> **Hypothesis 1.3**: *Storage is used more in perfect competition than in imperfect competition.*
>
> **Hypothesis 1.4**: *The more intermittent renewable energy generation is, the more storage increases social welfare.*

The model was applied for a stylized fifteen-node Western European electricity grid as presented by Gabriel and Leuthold [2010] to obtain qualitative insights. It was observed that **Hypothesis 1.1** is true for the perfect competition model of this thesis. This is a result of storage's price-smoothing effect, in which prices were observed to decrease more during high-demand periods than they increase during low-demand periods. However, it seems that in Cournot oligopoly, the increase in SW can also be caused by an increase in PS. This is, respectively, due to a larger increase in producers' revenue at off-peak hours than the decrease in high-peak hours is. Savings in ramp-up costs as a result of storage contribute here for their part, too. Consequently, in economic terms, storage seems to benefit society overall, but the benefit for market participants varies depending on the market setting and parameter assumptions. Based on a sensitivity analysis on price elasticity and renewable generation's uncertainty, the results for society's benefit are robust.

**Hypothesis 1.2** was confirmed for both perfect competition and Cournot oligopoly as measured by the profit of grid owners. That is, when there is storage capacity in the network, less transmission fees are being paid, and a conclusion that the lines are less congested can be drawn.

**Hypothesis 1.3** regarding the differences between non-strategic and strategic storage operation of producers seems to hold as well. It is optimal for strategic producers to curtail supply in order to raise market prices, and thus, their profit. In addition to conventional generation, producers are also able to reduce total supply by using less of their existing storage capacity than would economically be efficient. Furthermore, it was found that, in terms of imperfect competition's excessive pricing, storage is most beneficial for producers in CO compared to PC during peak hours.

Finally, no conclusive results about **Hypothesis 1.4** were reached. Storage is observed to have an economic benefit for society when there is intermittent renewable generation in the grid. However, the positive effect does not seem to depend on the volatility of wind generation. Thus, storage can be assumed to support society rather similarly regardless of whether renewable generation is uncertain or not. Nevertheless, the more there is uncertainty, the less uneven the distribution of welfare between producers and consumers is because producers are able to benefit from the presence of storage capacity, which increases their surplus. All in all, producers with storage capacity do not have to rely on ramping up their fossil fuel plants, which for its part supports the integration of green energy.

As discussed in the previous Section 4.3, the model has its limitations. These are particularly linked to the size and time frame of the numerical analysis. Both data and the network are too stylized to draw very in-depth conclusions for the real Western European market, as already highlighted by Gabriel and Leuthold [2010]. Additionally, the studied time-frame is relatively short, because a longer period would lead to a rapid growth of the scenario tree and possibly complicate computation. The purpose of this model is indeed to provide insights and something tangible to support decision making instead of modeling the operations on a very detailed level. Thus, looking into a more extensive and realistic network with longer modeling time frame is left for future research.

In addition, due to the indications that at least in some places electricity markets cannot be described as perfectly competitive, studying the strategic operations of storage owners in more detail would be of great importance. This could be done for different kinds of strategic models apart from Cournot oligopoly, such as a dynamic Stackelberg game or when only some of the companies are considered to have market power. Additionally, the effects of having strategic or non-strategic storage-only operations in the grid was not considered in this analysis, although the possibility has already been brought up by Schill and Kemfert [2011]. It has been a deliberate choice to carry out the numerical analysis with a realistic starting point for the production data. However, in the future there might be storage-only operators with even grid-scale capacity, and the surplus effects for them might significantly differ from those who also have conventional generation capacity. Another modification would be to study storage's market impacts on different kinds of markets, such as in bilateral markets.

Furthermore, before storage can be utilized to larger extent, grid-scale investments must be made and before anything, companies, producers, storage-only operators or maybe even grid-owners, need to have incentives to do so. One characteristic of electricity production is that it has a relatively high fixed cost ratio due to expensive plants and infrastructure, but the variable costs can be relatively low. Although the use of storage has been studied in this thesis from a short-term planning approach, another contribution would be to give insights on whether or not and for whom investments in storage capacity could be seen to be profitable in the long term. In addition, no operational storage costs were assumed in this thesis. Thus, one could look into the differences between storage technology types and see which of them would be the most appealing with current cost structures. Additionally, as stated by Pahle et al. [2013], one form of market power can be seen to be an exclusive access to a certain technology. They find that once conventional technologies are competitive and available to non-strategic players as well, strategic players do not want to invest them anymore. This is called "competitive technology reluctance" and occurs due to producer surplus decrease. If one wants to extend the idea cautiously into storage and see it as a form of market power, storage investments could be more likely if only strategic players are able to do so. However, the long-term aspects and investment focused research of storage can be seen as a future fields of research.

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