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Faculty of Social Sciences
Institute of Economic Studies

BACHELOR'S THESIS

Influence of renewable energy sources on transmission networks in Central Europe

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Declaration of Authorship

The author hereby declares that he compiled this thesis independently, using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Prague, May 10,2016

Signature

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Abstract

This thesis focuses on the influence of renewable energy sources on the transmission networks in Central Europe. Firstly, it gives an overview of the power and transmission systems of Central European states. Based on the analysis, three key causes of congestion and instability of the grid are identified. These include (i) insufficient transmission capacity between northern and southern Germany, (ii) Energiewende policy and (iii) existence of German-Austrian bidding zone. To assess the exact impact on the transmission grid, ELMOD model is employed. Two development scenarios for the year 2025 are evaluated on the basis of four representative weeks of the year 2015. The first scenario focuses on the effect of Energiewende on the transmission networks, the second one drops out nuclear phase-out and thus assesses isolated effect of increased solar and wind feed-in. The results indicate that higher feed-in of solar and wind power increases the exchange balance and total transport of electricity between TSO areas as well as the average load of lines and volatility of flows. Solar power is identified as a key contributor to the volatility increase, wind power is identified as a key loop-flow contributor. Eventually, it is concluded that German nuclear phase-out does not significantly exacerbate mentioned problems.

JEL Classification	L94, Q21, Q48, C61
Keywords	Energiewende, RES, transmission networks, congestion, loop flows, ELMOD, Central Europe

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Abstrakt

Tato práce se zaměřuje na vysvětlení vlivu obnovitelných zdrojů na přenosové sítě ve střední Evropě. Nejprve jsou popsány energetické a přenosové soustavy středoevropských států. Na základě této analýzy jsou pak identifikovány tři klíčové problémy, které přispívají k přetížení a destabilizaci sítí. Patří mezi ně (i) nedostatečná přenosová kapacita mezi severním a jižním Německem, (ii) politika Energiewende a (iii) existence německo-rakouské obchodní zóny. Pro posouzení těchto dopadů na přenosové sítě byl využit model ELMOD. Jsou porovnány dva scénáře vývoje pro rok 2025, a to na základě čtyř reprezentativních týdnů roku 2015. První scénář se zaměřuje na efekt Energiewende na přenosové sítě, druhý poté vynechává odstavení jaderných elektráren a posuzuje tak pouze dopady zvýšené produkce elektřiny ze slunečních a větrných zdrojů. Výsledky ukazují, že vyšší přítok energie ze solárních a větrných elektráren zvyšuje bilanci výměn a celkový transport mezi jednotlivými oblastmi TSO. Stejně tak roste i průměrné zatížení linek a volatilita toků. Klíčovým přispěvatelem k nárůstu volatility jsou solární elektrárny; větrné elektrárny jsou pak identifikovány jako hlavní příčina kruhových toků. Nakonec je zjištěno, že odstavení německých jaderných elektráren významným způsobem nepřispívá ke zhoršování zmíněných problémů.

Klasifikace JEL	L94, Q21, Q48, C61
Klíčová slova	Energiewende, OZE, přenosové soustavy, congestion, kruhové toky, ELMOD, střední Evropa

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Acronyms

AC Alternating current

ACER Agency for the Cooperation of Energy Regulators

AT Austria

CCGT Combined Cycle Gas Turbine

CCOT Combined Cycle Oil Turbine

CE Central Europe

CEE Central Eastern Europe

CZ Czech Republic

DC Direct current

DE Germany

DIW Deutsches Institut für Wirtschaftsforschung

EC European Commission

EEG Erneuerbare-Energien-Gesetz

EEX European Energy Exchange

ELMOD Electricity model

ENTSOE European Network of Transmission System Operators for Electricity

ERO Energy Regulatory Office

EU European Union

FiT Feed-in Tariff

GW(h) Gigawatt(hour)

kV kilo-Volt

MOE Merit Order Effect

MW(h) Megawatt(hour)

NTC Net Transfer Capacities

NPP Nuclear Power Plant

OCGT Open Cycle Gas Turbine

OCOT Open Cycle Oil Turbine

PL Poland

RES Renewable Energy Sources

SK Slovakia

TSO Transmision System Operator

TW(h) Terawatt(hour)

VAT Value-added Tax

VRES Variable Renewable Energy Sources

Bachelor's Thesis Proposal

Author	Jan Málek
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Consultant	Mgr. Lukáš Rečka
Proposed topic	Influence of renewable energy sources on transmission networks in Central Europe

Topic characteristics European power industry has undergone a very dynamic development recently. One of the reasons was the aim of EU political establishment to reduce energy dependency of Europe through generation of electricity from renewable resources. In the strategic document "Europe 2020", 20% of all electricity generation was predetermined to come from renewable resources until 2020. To reach this aim, set of incentive schemes was implemented, among others financial subsidies for renewable resources power plants.

As a result, precipitous growth of renewable electricity production has been observed in many countries. Such rapid change of energetic mix has brought wide range of challenges to energy sector. Many of them need to be still solved. Price distortions or instability and capacity of transmission networks are generally considered most serious examples of these challenges.

With respect to the fact that many papers were conducting research on the topic of renewables prices, I will focus on less inspected but same important issue of transmission networks in Czech Republic and central Europe region. In my thesis, I will try to discover how exactly the "renewables policy" influenced the functioning, stability, sustainability and cost of transmission network systems and what are the implications and perspectives for our nearest future.

Hypotheses

1. RES increase volatility of energy streams
2. RES increase cross-border flows of electricity

3. RES increase demands on price and amount of market regulators
4. RES increasingly contribute to destabilization of transmission networks in CE

Outline

1. Introduction
2. Literature review
3. Brief overview of central European transmission network and environment and its participants
4. Methodology and model
5. Data analysis and empirical evidence
6. Outcomes and possible solutions
7. Conclusion

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Chapter 1

Introduction

European power industry has recently undergone a very dynamic development. Among the environmental issues, one of the major drivers was the aim of EU political establishment to reduce energy dependency of Europe. With regard to fact that European fossil-fuel base and reserves are very limited[1], the only way of attaining the goal of increased self-sufficiency was the redirection of the energy sector towards locally produced energy coming from renewable resources.

Specifically, the strategy of the European commission, called "Europe 2020" presented on 3rd March 2010, set several targets for energy and enrironmental policies which are commonly known as 20-20-20 agenda. This means that by 2020, the EU aims to reduce its greenhouse gas emissions by at least 20% as compared to 1990, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more (European Commission 2009). Furthermore in 2014, this agenda was updated and even more ambitious targets in the form of 40-27-27 were set to be reached until 2030 (European Commission 2014a).

Another complex and ambitious project of the EU in energy sector is the effort to create a European Energy Union which was officially launched in 2015 European Commission (2015a). The project includes five main objectives (European Commission 2015b). In the context of this thesis, especially mentioning the objective of "fully integrated European energy market" (European Commission 2016) is worthwhile.

There are many different examples of market integration in the EU which

[1]According to the BP Statistical Review of World Energy 2015, reserves of EU countires account only for 0,3% of proved world oil reserves, 0,8% of proved gas reserves and 6,3% of coal reserves.

can be seen as precursors of future integrated market. One major example in the region of Central Europe is the bidding zone of Germany and Austria[2].

Nevertheless, as can be seen in this thesis, mentioned policies and objectives are, under the current situation in the energy sector, quite in a contradiction. A rapid increase of renewable energy sources has brought wide range of challenges to whole electricity sector. Price distortions, instability of supply or capacity of trasmission networks are generally considered to embody the most serious examples of these challanges. At the same time, inappropriate delineation and integration of the market contributes furthermore to mentioned problems instead of eliminating them.

In the context of Central Europe, this can be demonstrated followingly. With the development of solar and wind power plants in Germany, severe problems with transmission occured. Excess production in the north has to be transported to the consumption centres in the south and to Austria and other energy deficient countries in southern Europe. The existing German grid is not able to accomodate such a big feed-in of intermitent renewable energy and, therefore, exhibits congestion. As a result, electricity flows through the systems of adjacent countries, Poland and the Czech Republic, and causes severe problems in their grids as well. Furthermore, these problems are exacerbated by the market integration, in particular by the existence of German-Austrian bidding zone which enables these two countries to trade electricity disregarding the physical grid constraints. Illustration is given in the figure 1.1.

The Czech, Polish and Slovak TSOs are, naturally, dissatisfied with the state of current affairs as nobody compensates the expenses that have to be incurred to tackle this problem. Whole situation becomes subject of heated debates on the highest political levels. While Czech and Polish TSOs strive for splitting up of the bidding zone (ČEPS *et al.* 2012)[3], or even for splitting up Germany in more zones, Austrian bodies oppose this and try to avoid such solution as it would significantly increase the cost of electricity there. Except the political measures, TSOs also attempt to solve this problem by installing phase-shifting transformers that should be able to stop the physical electricity flows in case of emergency. On this example, we can see that higher amount of installed VRES capacities induces grid congestion. Therefore, attaining both proposed strategies of the EU is incompatible.

[2]Definition of bidding zone as well as other examples of market integration are given in the section 2.4

[3]This split was also recommended by the Agency for the Cooperation of Energy Regulators in September 2015. More details can be found in section 2.4.3

Figure 1.1: Stylized map of situation in CE

Source: Author, based on maps from ENTSOE (2016a)

With respect to the fact that many academicians conducted research on the topic of influence of renewables on spot or forward market prices of electricity (Traber & Kemfert (2009); Cludius *et al.* (2014); Ketterer (2014); Meyer & Luther (2004)), attention will be drawn to less inspected, but equally important transmission networks issues.

Majority of the literature models and assesses the transmission network issues in the context of Germany (Burstedde (2012); Kunz (2013); Kunz & Zerrahn (2015); Schroeder *et al.* (2013); Egerer *et al.* (2014); Weigt *et al.* (2010); Dietrich *et al.* (2010)). The contribtuion of this work is that, unlike many others, it focuses on the whole region of Central Europe in the same detail as Germany and particularly elaborates on the inlfuence of individual components of Energiewende policy (i.e. renewable energy promotion and nuclear phase-out) on the whole area. Furthermore, this thesis stresses the importance of German - Austrian bidding zone which is mostly neglected in research.

With regard to what was mentioned in previous paragraphs, there are two key hypotheses in this work: i) Increased VRES feed-in and nuclear phase-out[4] contribute to cross-border grid congestion in Cetral Europe and ii) Increased VRES feed-in and nuclear phase-out cause volatility growth and thus contribute to the destabilization of transmission networks in Central Europe.

Moreover from a conceptional point of view, this work should be seen as a "critical scenario approach". This means that the results must be interpreted in the context of would be the impact of flows on the grid if nothing was done in their development.

The thesis is structured as follows: Chapter 2 gives basic information about the power and transmission systems of Central European states and introduces brief history of renewable energy develompment in mentioned countries. Furthermore, explanation of the mechanics of current regional market design with attention paid to the bottlenecks is included. Based on this, loop and transit electricity flows are examined and a connection to the implementation of renewables to power grids is shown. Chapter 3 covers the work of other researchers on this topic. Chapter 4 contains the formulation, explanation and application of the model as well as the description of datasets. It also focuses on the definition of scenarios. Chapter 5 presents the results. Finally, Chapter 6 summarizes the findings.

[4]Increased VRES feed-in and nuclear phase-out are both essential parts of Energiewende policy. Because of the major role of Germany in Central European power industry, Energiewende is taken as an embodiment of both factors.

Chapter 2

Overview of power and transmission systems

2.1 Czech power system

2.1.1 Current situation

After Germany and Poland, the Czech Republic's production of electricity is the third largest in the region of CE which is a stable trend as the ordering has not changed since the birth of the Czech Republic in 1993 (EUROSTAT 2016).

According to the Energy Regulatory office (ERO), 86003.4 GWh of electricity was generated in all power plants during 2014 in gross terms. When considering the losses and electricity needed for own generation, 79885.9 GWh was left at disposal (Energy Regulatory Office 2015). The biggest contributors to total production were solid fuels and nuclear power plants. The exact production pattern is depicted in figure 2.1.

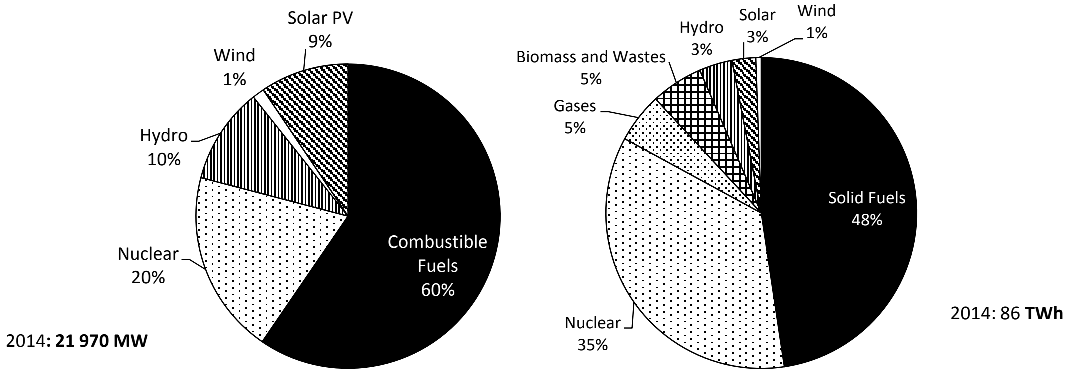
At the same time, net balance with foreign countries accounted for 16300 GWh of export[1] which maked the Czech Republic the third largest exporter of electricity in Europe (Energy Regulatory Office 2015).

Production shares

After having summarised total numbers, we can proceed to their decomposition to see the sources and, above all, general trends in production. Czech power industry has traditionally been based on home natural resources which are,

[1] According to the previous year's ERO reports, the only year when Czech Republic became net electricity importer was the year 1995. Moreover, the balance with other countries did not decline under 11 TWh since 2002.

Figure 2.1: Installed capacity and electricity generation in the Czech Republic



(a) Installed capacity as of 31.12.2014 (b) Electricity production by fuel type 2014

Source: European Commission, DG Energy (2016a)

however, scarce to a large extent. Thus, the only resources available historically in reasonable quantities were fossil fuels (hard coal and brown coal[2]) and uranium. Dominance of these resources in the Czech energy mix can be seen throughout the years (figure 2.2)

2.1.2 Renewables in the Czech Republic

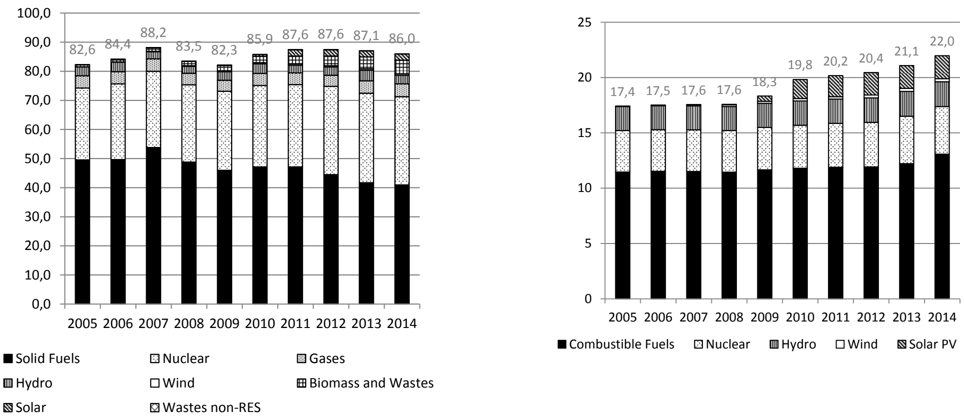
Since the introduction of renewable target, Czech power industry had to react and try to diversify the electricity portfolio to comply with the 13% renewables target set by European commission for the Czech Republic (European Commission 2009). As a response, certain reduction of traditional power plants fuels occured to the benefit of renewable energy sources (RES)[3], especially photovoltaics, wind and biomass. Advancement of these particular types of renewable energy is given by several factors. First of all, with respect to the fact that Czech Republic is a landlocked country on stable tectonic plates and fully exploited "poor hydro energetic potential"[4] (Pačes 2008), utilization of

[2] Nevertheless, reserves of coal are, de facto, very constrained as a consequence of mining limits which are imposed on deposits in northern Bohemia.

[3] In Czech legal framework, definition of RES can be found in the article 2 of the act 165/2012 Coll. and states following: "As renewable non-fossil natural resources are considered wind energy, solar energy, water energy, geothermal energy, air energy, biomass energy, landfill-gas energy, sewage treatment plant gas energy and biogas energy".

[4] Potential was quantified to reach only 350kWh/hectare mainly due to the fact that the Czech Republic is the river-source area. (Pačes 2008)

Figure 2.2: Historical overview of installed capacities and electricity generation in the Czech Republic



(a) Gross Electricity Generation by fuel, TWh (b) Installed generation capacity, MW

Source: European Commission, DG Energy (2016a)

tidal, geothermal or further hydro power was not feasible. Hence, solar power, wind and biomass remained as the only possibilities.

Brief development of Czech renewable energy

Even though the actual boom of RES, especially photovoltaics, and corresponding transmission grid problems began in 2009, we have to go back to 2006 and subsequent years for a full reasoning. In 2006, The Act on the Support of Electricity from Renewable Energy Sources (Vláda ČR 2005)[5] was introduced as an implementation of the Directive of European parliament no. 2001/77/EP. In this document, we can find explicitly stated obligation of the transmission or distribution system operator to connect such sources into the grid[6] and buy electricity from such producers (Vláda ČR 2005). Moreover, generous subsidization schemes in form of feed-in tariffs with strong irrevocability rules[7] were also included. In few subsequent years, particularly in 2008, several other factors contributed to the later acceleration. Bechník *et al.* (2010) and Průša *et al.* (2013) speak about three factors - appreciation of Czech Crown up to

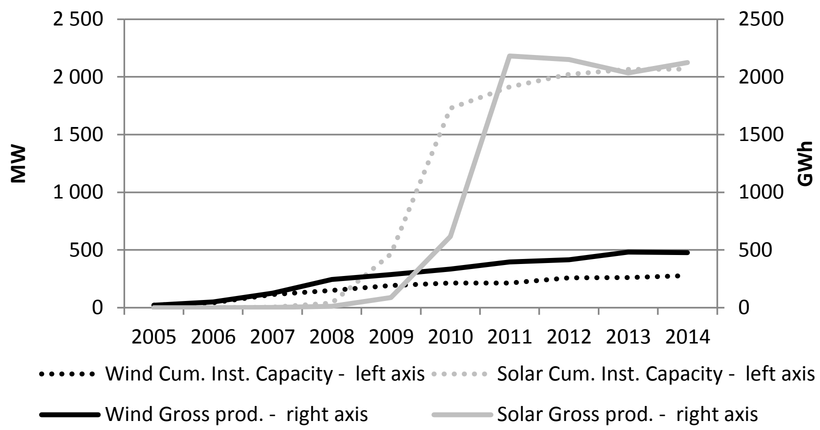
[5]It is important to mention that this Act 180/2005 Coll. was abolished on 1st Jan 2013 and replaced by the act 165/2012 Coll.

[6]The only exception was the case when local grid capacity was not sufficient

[7]In Paragraph 6 of Act 180/2005 Coll, it was stated that the feed-in tarif is set so to guarantee the payback period to be shorter than 15 years. At the same time, prices were guarantedd for 15 years (later extended to 20) and price reduction was constrained at maximum of 5% per year.

23,7 CZK per Euro, 20% fall of prices of solar panels and extension of feed-in tariff guarantee from 15 to 20 years.

Figure 2.3: Solar and Wind development in the Czech Republic



Source: European Commission, DG Energy (2016a)

In figure 2.3, afore mentioned extreme growth of installed capacity of solar power plants can be seen between 2008 and 2012. In this period, the cummulative capacity grew little more than 50 times! To further illustrate the seriousness of the situation, only during 2009 and 2010, applicants asked the distribution companies to connect up to 8000 MW (Vrba *et al.* 2015) which resulted in the request of Czech transmission system operator, the company CEPS, to temporarily stop the approvals of new capacities (ČEPS 2010b). Despite the fact that this step was strongly opposed by many solar investors, it was rational outcome of the situation[8]. After such critical situation, Czech political elites were forced to act quickly. Changes in laws were made in order to stabilize photovoltaic base[9]. After that, approvals for connections to the grid were allowed again in January 2012 (Klos 2012).

This piece of experience illustrates, on quite a small local scale, one of the most serious issues that will be of greatest interest in further work - the influence that some RES have on transmission networks. By the word "some", primarily "variable renewable sources" including wind and solar power plants are

[8]In the energy study of the company EGU, maximal safe installed capacity of variable energy sources is set to 1650 MW between 2010-2012 and 2000 MW between 2013-2015.Thus, from this perspective, security was endangered already in 2010 (1727 MW of solar and 213 of wind installed)(EGÚ Brno 2010)

[9]Prices were decreased up to 50% by an amendment and, later, feed-in tariffs were completely abolished for most power plants (Vrba *et al.* 2015)

meant. The reason is that unlike traditional and other RES power plants, these two types of plants have completely different requirements on the construction and management of networks that vary greatly from our present centralized transmission system models.

Transmission network models

In the existing centralized model, several large-scale electricity production units exist (installed capacity from hundreds to thousands of MW) with controllable and rather stable output supplying final-consumers for even quite long distances. Transmission of electricity is thus one-way - from a producer to a consumer.

Unlike the production units in this model, variable RES are based on many small and scattered production units delivering small, intradaily volatile and hardly predictable amount of electricity, depending on surrounding weather circumstances.

System, that can absorb such flows, is called decentralized. In the decentralized model, combination of central large-scale power plants with local production is used. In case of controllable RES like biomass or waste incinerators, small water plants or cogeneration units, no serious integration problems occur. Nevertheless, when moving to photovoltaics or wind, enhanced transmission and distribution grids with some elements of electricity storage are necessary to accomodate the needs of all market agents. Such grids are called "smart grids".

The essential challenge lies in the fact, that "smart grids" are not available almost anywhere and thus current centralized model must be used. All further work has this set-up as inbuilt assumption.

2.1.3 Czech transmission system

Czech transmission system consists of country-wide control area which is under the maintenance of the Czech transmission system operator, state - owned company CEPS. According to the TSO, Czech backbone transmission system constitutes of 3510 km of 400 kV lines and 1909 km of 220 kV lines which were finished in the 1980s and 1970s respectively. In addition, the system comprises 41 substations with 71 transformers for both basic voltage levels. The transmission network serves three purposes. Firstly, it transmits electricity throughout the whole Czech Republic. Secondly, it supplies electricity to distribution networks from which electricity is then delivered to final consumers[10]. Thirdly, it is part of European international transmission network (ČEPS 2016b).

Figure 2.4: Czech transmission network

Source: ČEPS (2016b)

CEPS, as a TSO, has several key responsibilities. Primarily, it is legally obliged to ensure the stability of the grid by balancing the supply and demand of the electricity. Next, it is in charge of maintenance and development of the grid. Eventually, it administers the transmission of electricity between the producers and distributors of electricity and collaborates with foreign TSOs (ČEPS 2016a).

Grid development

Due to the fact that the backbone transmission system in the Czech Republic merely reflects the design at the time of completion at end of the 1980s, investments to the grid enhancement and reinforcement need to be done so that the grid is able to cope with upcoming challanges[11]. CEPS is well aware of this fact and thus develompnent of the grid is among its indispensable, ongoing activities (ČEPS 2016c).

The process of planning the further development is mostly driven by the "Ten-year investment plan for the development of the transmission system".

[10]In the Czech republic, distribution is ensured by there companies: PRE distribuce, a.s., CEZ distribuce, a.s., E-ON distribuce, a.s.

[11]Exact factors that are anticipated to affect the decision about grid investment are given in ČEPS (2016c)

Current plan works with the time scope of 2015-2024. Following objectives are defined in the document:

a) system sections necessary to be constructed or extended in the following 10 years

b) all investment projects already decided by the company to be implemented, including implementation schedule

c) new investment projects to be implemented in the following 3 years, including implementation schedule (ČEPS 2015b)

Especially the objective a) is of the greatest concern due to the international-related impacts on the Czech transmission system as will be shown in the sections 2.2 and others. Pursuant to its legal obligation, CEPS prepares the implementation of measures aiming to ensure system stability. These include expansion and upgrade of existing substations, construction of second circuits on selected lines as well as building of several new ones. Installation of phase-shifting transformers at Czech-German interconnectors counts also to considered options (ČEPS 2015b). Detailed list of intended projects can be found in ČEPS (2016c). The total volume of investment funds for these projects amounts to CZK 44.90 bn (ČEPS 2015b).

2.2 German power system

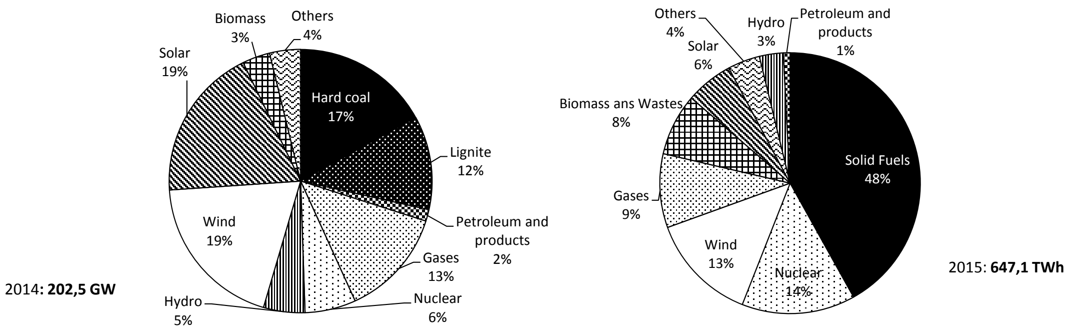
2.2.1 Current situation

Germany is an absolute leader in the amount of produced electricity in CE as well as in Europe in general (EUROSTAT 2016). This position has been maintained for several decades.

Based on the data from German Ministry of Economy and Energy (BMWi), 651.6 TWh of electricity was produced in Germany during 2015 (BMWi 2016). The share of solid fuels is similar to Czech Republic, with the only difference that almost 57% of such electricity was generated by burning brown coal. It is also worth mentioning that renewables accounted for 30 % of the total electricity production. Out of this, the most important sources are on shore wind turbines, biomass and solar power plants.

Due to the fact that Germany is a federation of several states and its electricity production represents major share of whole CE production, it is desirable

Figure 2.5: Installed capacity and electricity generation in Germany

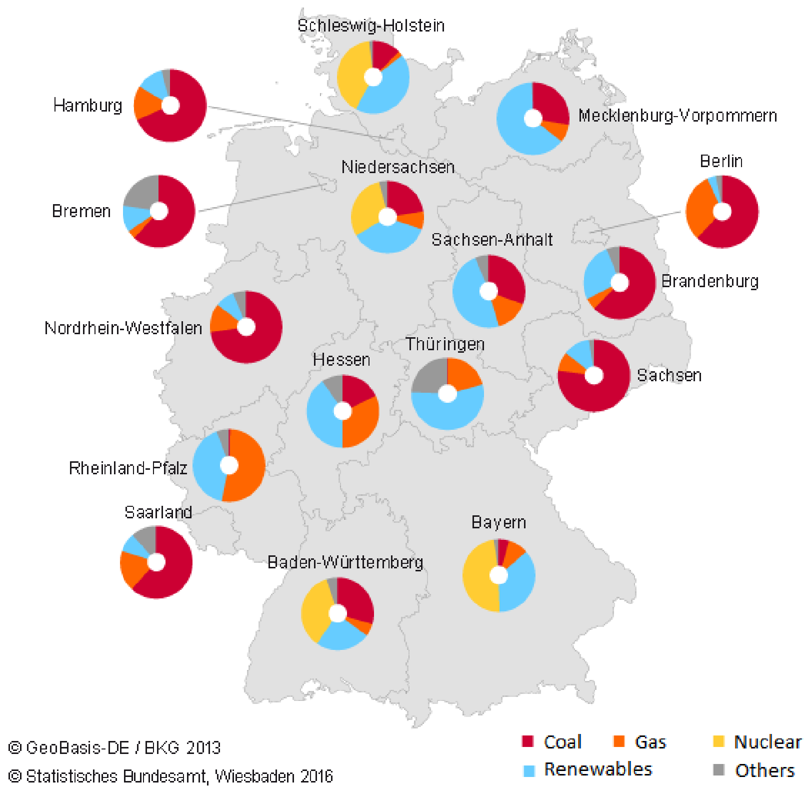


(a) Installed capacity as of 31.12.2014 (b) Electricity production by fuel type 2015

Source: BMWi (2016)

to have a look at the electricity production in particular federal states as this varies a lot (figure 2.6).

Figure 2.6: Electricity generation by types in particular Federal states



Source: Statistisches Bundesamt (2016)

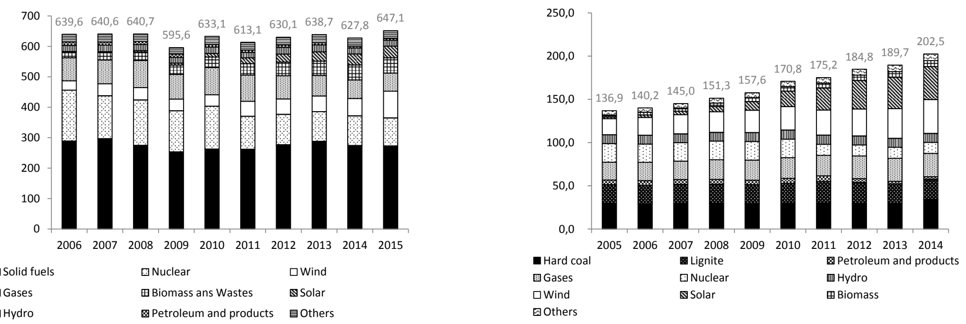
From the standpoint of installed capacity, German energy sector appears to be quite progressive. At the end of 2014, 46.72% of total installed capacity can be assigned to renewable energy sources. This is a second highest number[12] in the CE region.

Germany has been also net electricity exporter in the long run[13]. Even though the amount fluctuates throughout years, Germany exported 50.1 TWh of electricity in 2015 (BMWi 2016).

Production shares

Likewise the Czech Republic, Germany has very limited natural resources. Among the feasible ones, brown and hard coal are of greatest importance. The historical power mix corresponded to such resources allocation; most of electricity was generated by coal and nuclear power plants (see figure 2.7). Nevertheless, the situation started to change in early 90s when Germany decided to pioneer in bringing renewables to the life and started the energy transition, later called Enegiewende[14].

Figure 2.7: Historical overview of installed capacities and electricity generation in Germany



(a) Gross Electricity Generation by fuel, TWh (b) Installed generation capacity, MW

Source: BMWi (2016)

2.2.2 Renewables in Germany - Energiewende

German renewable story differs from the Czech case to a large extent. Firstly, it has much longer history and, secondly, much more significant volume as

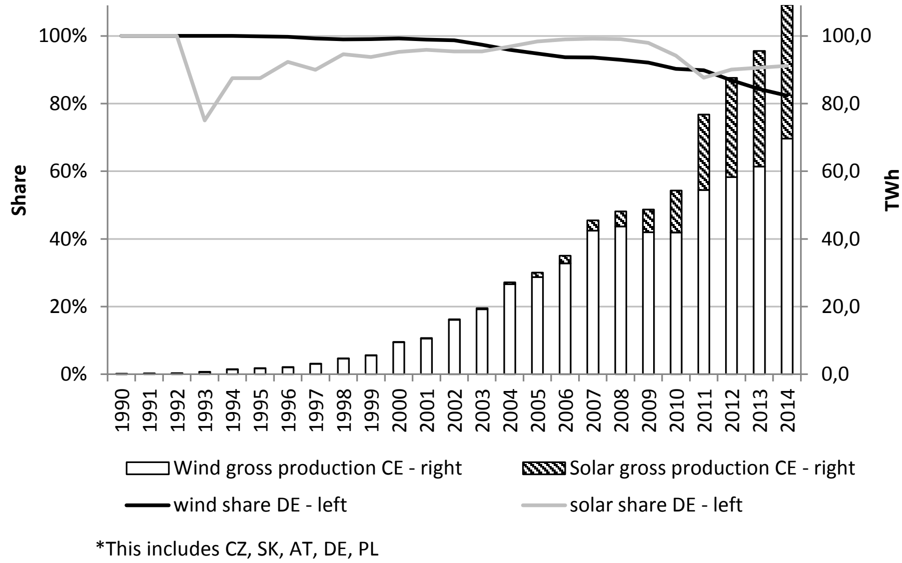
[12] Austria produces the largest share of electricity from renewables.

[13] Germany was net importer in 2002 for the last time

[14] The term "Energiewende" (which we translate here as "energy transition") did not just come about in the past few years. In fact, it was coined in a 1980 study by Germany's Institute for Applied Ecology (Morris & Pehnt 2012)

Germany is, in general, the biggest producer of electricity in CE. The latter feature is shown in the next figure 2.8:

Figure 2.8: Wind and solar production in CE* and share of Germany



Source: Own, data European Commission, DG Energy (2016a)

Consequently, German decisions and actions about energy policies affect whole region fundamentally. For this reason, we will have detailed look at the German power and transmission situation.

Brief history of Energiewende

The history of German[15] energy transition dates back to the early 1970s when opposition against conventional, especially nuclear, power plants stated to crystalize in German society. The factor that significantly strengthened this movement was the planned construction of nuclear power plant in the town of Wyhl (Morris & Pehnt 2012). Since these public upheavals in Wyhl in 1973, which were further exacerbated by 1986 Chernobyl accident and 1997 Three Mile Island accident, persistent opposition to nuclear energy have been flourishing[16]. In the Chernobyl aftermath, some political parties, namely SPD and The Greens, started to reflect this stance by altering the course towards nu-

[15]We talk here about the West Germany, officially Federal Republic of Germany

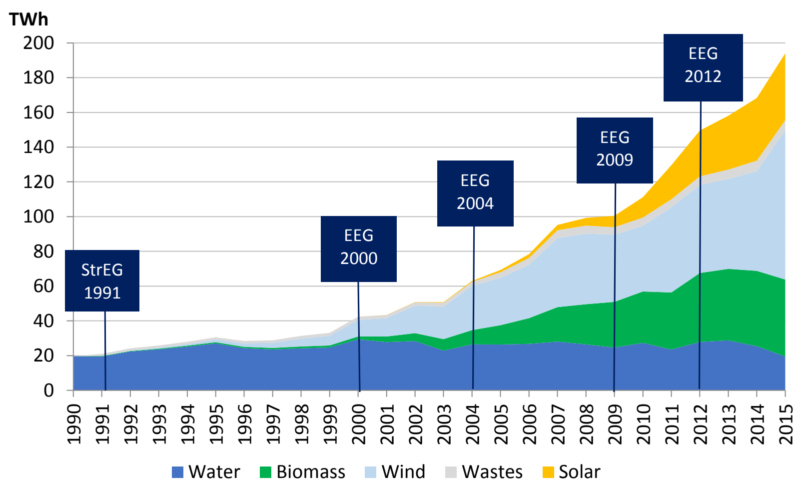
[16]Right after the Chernobyl crisis, 86% of Western Germans were in favour of nuclear phase out (Hake *et al.* 2015)

clear phase-out and environmentalism, in particular RES support (Hake *et al.* 2015; Černoch *et al.* 2015).

Practical implementation of RES support came into force on 1 January 1991 in the form of Grid Feed–In Law[17]. This was a first attempt to implement predecessors of feed-in tariffs (Lang & Lang n.a.).

Since this period, we can see gradual increase of RES installed capacity which was considered as very slow in the eyes of German public. An answer came in 2000, when much subtle law, Renewable Energy Act[18] , was adopted by SPD and Greens administration and replaced StrEG. According to Morris & Pehnt (2012), the main difference between this Act and the Feed–in Act of 1991 was that feed–in tariffs (FiT) were no longer linked to a percentage of the retail rate, but were instead differentiated by the actual cost of the specific investment in terms of system size and technology type. Moreover, the grid operators were obligated to accept electricity from third-party renewables, to feed in the electricity and to pay the fixed prices. FiT were guaranteed for 20 years. The cost of the FiT is covered as a surcharge on final customer electricity bills[19]. Figure 2.9 gives a graphical summary of above mentioned development.

Figure 2.9: Gross renewable electricity generation and and development of energy laws



Source: Own, data European Commission, DG Energy (2016a)

On top of that, second aspect of Energiewende, nuclear phase-out, was

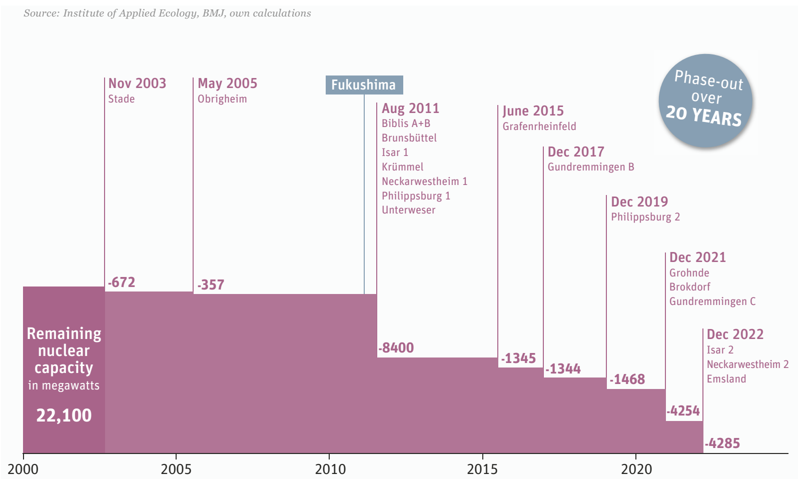
[17]Stromeinspeisungsgesetz, StrEG

[18]Gesetz für den Ausbau erneuerbarer Energien (EEG)

[19]It is evident that Czech RES laws sought a lot of inspiration in EEG as eminent features are very similar

implemented and scheduled to be completed in 2022 (Morris & Pehnt 2012). The agreement between Government and major power utilities companies was negotiated even despite the fact that the companies had no right to any kind of compensation. The deal was made so that the lifetime of existing nuclear power plants (NPP) was limited to 32 years on average, and on this basis every NPP was granted so called residual electricity volume. The effective date for the beginning of the remaining terms was determined retrospectively on 1 January, 2000. However, the government made it possible to transfer left-over power quantities from unprofitable (older) to profitable (younger) power plants (Hake *et al.* 2015). Phase-out schedule can be seen in the picture 2.10.

Figure 2.10: Nuclear phase-out in Germany



Source: Morris & Pehnt (2012)

Another amendments of the EEG were made in 2004, 2009 and 2012[20] which further induced investment into the RES and led to their sharp increase observable in recent past. In 2010, simultaneously with EEG, Merkel's administration introduced document known as "Energiekonzept"[21] where ambitious short run and long run goals of Energiewende were defined (Hake *et al.* 2015). These goals also complied with European Directive 2009/28/EC. Overview can be found in the table 2.1.

[20] 2004: improved legal status of operators of RES power plant + feed-in tariffs modified (inclusion of solar power). 2009: requirement on builders to implement renewable heating systems. 2012: encouragement of direct marketing. Option between feed-in tariff and market premium Lang & Lang (n.a.)

[21] Full name: Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung

Table 2.1: Electricity related Energiewende goals

	2020	2030	2040	2050
Greenhouse gas emissions (compared to 1990)	at least -40%	at least -55%	at least -70%	at least -80% to -95%
Gross electricity consumption (compared to 2008)	-10%	-25%	-25%	-25%
Share of electricity generation from combined heat and power plants	25%			
Share of RES on electricity consumption	more than 35%	more than 50%	more than 65%	more than 80%
Source:	(BMWi 2015b, p.7)			

Consequences of StrEG, EEG and Energiekonzept

German concept of Energiewende delivered both success and problems. In the first case, we can see that installed capacity as well as production from renewables is important part of electricity mix nowadays which is in accordance with set goals. Following table 2.2 gives us an overview of the effects of StrEG and EEG on the growth of RES sources.

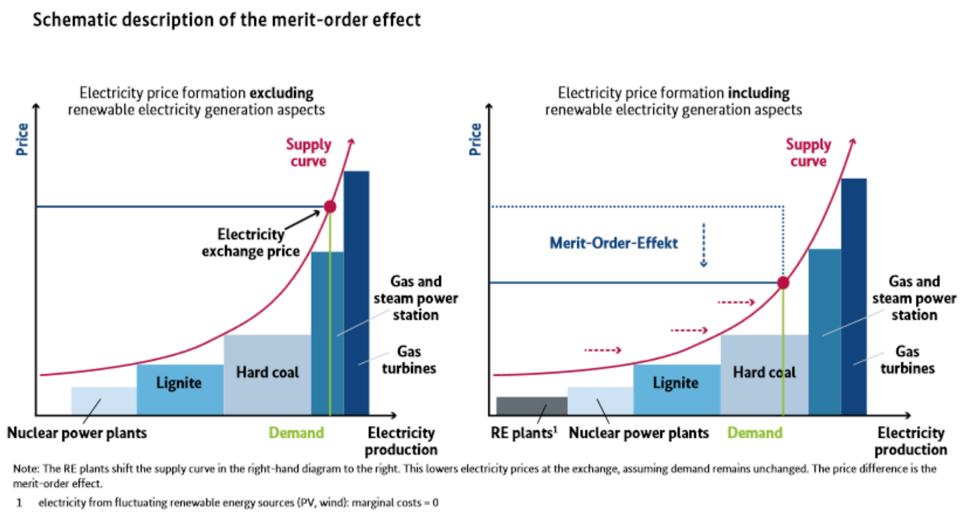
Table 2.2: Growth of renewable production under different laws

	From 1991 to 2000 (StrEG), TWh		From 2001 to 2014 (EEG), TWh	
Gross production	Absolute growth	Average yoy growth	Absolute growth	Average yoy growth
Wind	9,4	0,94	46,5	3,10
Water	9,9	0,99	-3,1	-0,21
Biomass	1,3	0,13	41,4	2,76
Solar	0,0	0,00	34,9	2,33
Wastes	0,6	0,06	4,3	0,28
Data source:	BMWi, 2014			

On the other hand, all this success is owed to the munificent subsidization policy that was incorporated in laws from the very beginning. There are numerous studies that attempted to assess the scheme from the perspective of expenses by various methods. Although it is not the aim of this thesis to analyse these aspects deeper, there is certain necessity to sketch basic findings.

The results are in general the same - RES decrease price of electricity in futures markets and increase their volatility in a spot markets (Ketterer 2014; Keles *et al.* 2013). At the same time, consumers have to face surcharge that significantly raises final prices. As a result, price distortions and redistributions occur on the electricity market (Cludius *et al.* 2014). Mentioned principle follows from so called merit order effect (MOE)[22] which is depicted in the figure 2.11.

Figure 2.11: Merit order effect



Source: BMWi (2015b)

The MOE lowers prices on exchange markets as RES start producing[23]. Crowding out of producers occurs whose marginal production costs are the highest[24]. Subsequently, renewables and cheapest conventional sources are left on the market; the more expensive ones are able to cover the costs only during the peak-load times. The distortion and redistribution is grounded in the surcharge that is paid to RES producers at the same time[25] (Cludius *et al.* 2014). At the end, this set-up implies very interesting paradox. Whilst the market price in Germany is one of the lowest in Europe, prices for households and production sector are one of the highest (Černoch *et al.* 2015).

Another issue of eminent importance that comes along with Energiewende is connected to the set-up of the power and transmission systems whose nature has been challenged since the sharp increase of RES production. The main problem lies in the fact that RES plants, especially solar and wind ones, are situated

[22]Merit order effect describes the lowering of power prices at the electricity exchange due to an increased supply of renewable energies. Power suppliers of renewable installations have almost no operating costs (since they do not need fuel or much manpower). That means they lower the entrance price and push more expensive conventional producers out of the market (Appunn 2015)

[23]In 2013, MOE was estimated to account 3 Bn Eur (Breitschopf *et al.* 2015)

[24]in principle hard coal, gas and oil power plants (Cludius *et al.* 2014)

[25]According to BDEW, total EEG surcharge accounted for 18.78, 23.68 and 21.82 Bn EUR without VAT in 2013-2015 respectively BMWi (2016).

in the places where natural conditions are the best. In addition, these sources require treatment which completely differs from the conventional controllable resources. The major differences were described in the previous text. The biggest problem of Energiewende concept was the fact that this aspect was practically not solved. As a result, an enormous inflow of renewable current has to be incorporated into the system which exemplifies primary issue of today's energy industry.

Reform of EEG

Before we proceed to the German transmission system, it is necessary to mention how were described Energiewende drawbacks reflected by political representation. In August 2014, major reform of EEG took place. The incentives were threefold.

1. To do something about the enormous price for final customers
2. To reduce the market distortions coming from the FiT based subsidization
3. To solve unbearable situation about transmission flows (Lang & Lang n.a.)

In the first place, net annual growth corridors for each type of power plants were set[26] which should have contributed to better control of installed capacity. Also, the surcharges were tied to the obedience of the rules for the corridors. In the second place, FiT were declared to be removed by system of market feed-in premiums which should force producers to behave more on market basis (Černoch *et al.* 2015). Last but not least, EEG 2014 dedicates several paragraphs to legal obligation of TSOs to ensure proper grid connections.

2.2.3 German transmission system

German power grid seems to exhibit much more complexity than the Czech one, which should be of no surprise as both the amount of electricity and area of Germany are much greater than in the Czech case. The grid consists of four stages. Three are subject to distributional grid and one, extra high voltage grid (220 kV and 380 kV), embodies the transmission system. Total length of the

[26] Onshore wind power: net annual growth corridor target of 2500 MW; Offshore wind power: reduction of the national targets for offshore wind power from 10 GW to 6.5 GW by 2020 and from 25 GW to 15 GW by 2030; Solar power: gross annual growth corridor target of 2500 MW; Biomass: gross annual growth corridor target of 100 MW (Lang & Lang n.a.)

transmission network accounts approximately for 35200 km (Flechter & Bolay 2015).

There are four TSOs in Germany. Each of this companies was previously owned by one of the big four utilities. There have been, however, a number of changes to the ownership structure in recent years, as the big utilities divested transmission assets for a number of reasons, including regulatory pressure of the European Commission[27] and German government[28]. This have poured out into the sale of assets to independent shareholders or legal unbundling from the parent company (IEA 2013). Resulting list includes following operators: TenneT, Amprion, 50Hertz Transmission and TransnetBW. Some further details about the operators can be found in the table 2.3. Graphical division of areas of operation is shown in the figure 2.12.

Figure 2.12: Transmission system operators in Germany

Source: Feix *et al.* (2015)

Likewise in the Czech Republic, TSOs are responsible for the secure transmission of energy, constant monitoring of the balance between the demand and supply and intervening in the market if necessary. In addition, they are respon-

[27] We refer here to the unbundling initiative anchored in the The European Electricity Market Directive (Directive 2009/72/EC).

[28] According to Energy Industry Act of 2005 (Energiewirtschaftsgesetz, or EnWG), transmission and supply were required to be unbundled starting in 2005 (Agora Energiewende 2015)

Table 2.3: German transmission system operators

Name	Ownership pre-unbundling	Ownership after unbundling	HQ	Area km squared	Population milions	Lines km	Transformer stations
TenneT	E.ON	State of The Netherlands, 100%	Bayreuth	140 000	20	10 700	115
50Hertz	Vattenfall	Elia and Elia Asset 60%; IFM 40%	Berlin	110 000	18	9 840	75
Amprion	RWE	RWE 25.1%, Commerz Real AG 74.9%	Dortmund	73 100	27	11 000	160
TransnetBW	EnBW	EnBW 100%	Stuttgart	34 600	11	3 363	80
Source:	Feix *et al.* (2015), IEA (2013), Agora Energiewende (2015)						

sible for the maintenance of the grid and its expansion as needed (TENNET n.a.). The TSOs are supervised and regulated by the German federal network agency, Bundesnetzagentur (BnetzA) which ensures discrimination free grid access and, since 2011, has also played an essential role in implementing the grid expansion codified in the Grid Expansion Acceleration Act (NABEG).

Challanges to German grid

As we sketched earlier, German transmission grid faces severe problems. In the past, electricity generation was based on two criterions: Availability of resources in place or in proximity and close location to the demand. The first case can be observed on the distribution of coal power plants in coal reservoirs in western and eastern Germany, the latter case can be seen on the existence of nuclear power plants in southern Germany (Flechter & Bolay 2015).

Today, the main challenge lies in the complete transition from the old model as many bottlenecks and congestion in the transmission system occur. The reasons are twofold. Firstly, there is the goal of increasing electricity production from renewables[29]. Centres of electricity consumption situated mostly in the south and west of the country seldom overlap with regions suitable for most economic production of renewable electricity. These are located in the north of Germany where, on the contrary, electricity consumption is low. The electricity generated there must therefore be transported over long distances to the consumers in north-south way. In the process, the existing network is frequently reaching its capacity limits (Bundesnetzagentur 2015).

The second goal, related to nuclear phaseout, further contributes to the north-south grid pressures. Nuclear power plants are mostly located in southern regions, Bavaria and Baden-Württemberg, as can be seen from the map 2.6.

[29]The greatest RES increments are projected to come from off-shore wind turbines in the North Sea

To be more specific, 8386 MW of nuclear installed capacity in these two states should be disconnected from the grid by 2022. The loss of capacity is not expected to be fully offset by new installed capacities, which is the result of limited RES potential (Flechter & Bolay 2015).

Having seen the effects of planned energy transition in form of increase of capacities in the north and its decline in the south and combining it with the current situation of intra-German electricity balance[30], the necessity of strengthening the infrastructure in north-south direction is unquestionable. This is also a standpoint of both, German authorities (BMWi 2015a) and especially neighbouring TSOs[31]. Nevertheless, the volume of the infrastructure extension as well as the realization itself seems to be a matter of controversy and contributes thus to prolongation of problems.

The grid expansion agenda is backed by two laws - Power Grid Expansion Act (EnLAG) from 2009 and Federal Requirements Plan Act (BBPlG)[32] of 2013.

EnLAG legislature specified 23 mostly north-south transmission lines in the length of 1876 km that need to be urgently built to preserve the stability of the system in the environment of increasing RES production. The construction should have been finished by the end of 2015 (Flechter & Bolay 2015). Nonetheless, in the second quarter of 2015, only 8 kilometers of lines were built which gives 487 km with previous construction. Estimates now calculate with 40% being built till the end of 2016 (Bundesnetzagentur 2016). BBPlG, which came into effect in July 2013, added another 36 planned extension lines out of which 16 are considered of cross-regional or cross-border importance. Corridors of future networks are now determined and a public discussion about the exact tracing is in progress (BMWi 2015c).

Mainly EnLAG activities take up major project delays which can be ascribed to the negative public opinion and resistance which accompanies the network construction[33]. The general public refuses the grid construction in the

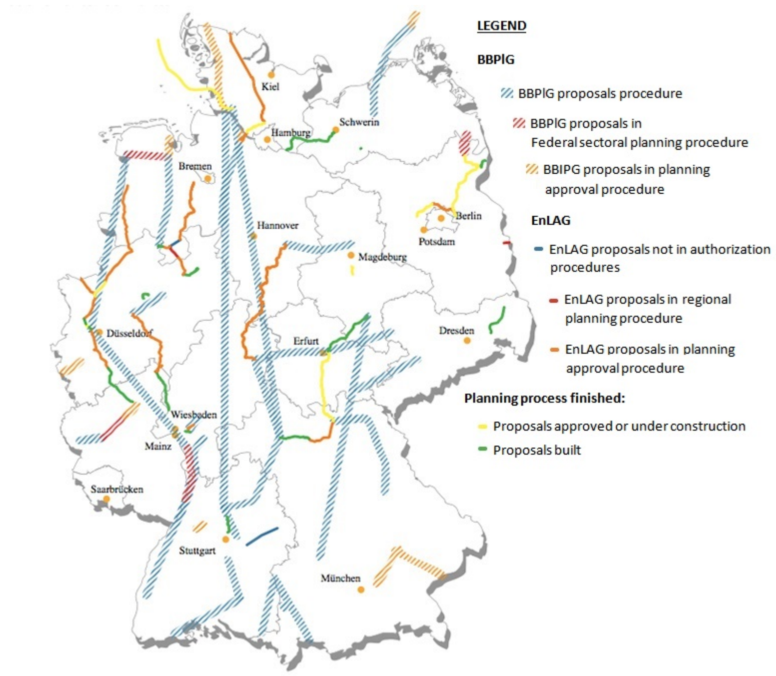
[30]The balance design is such that southern regions import electricity whereas norther regions export it.

[31]The international dimesion of this issue - so called loop flows - will be shown next subchapter

[32]EnLAG stands for Gesetz zum Ausbau von Energieleitungen, BBPlG stand for Bundesbedarfsplangesetz

[33]A lot of commotion is present at the realization of biggest north-south oriented lines. Examples can be found here: http://www.ft.com/cms/s/0/756454dc-a2d6-11e3-ba21-00144feab7de.htmlaxzz3razksGUb or here: http://www.faz.net/aktuell/wirtschaft/wirtschaftspolitik/netzausbau-so-kommt-der-oekostrom-in-den-sueden-12786111.html

Figure 2.13: Future extension of German transmission lines



Source: BMWi (2015c)

vicinity of their places of living and requires mostly the underground cable solutions[34,35]. This is, to a certain extent, interesting paradox as wind and solar parks have previously been mostly approved[36]. As a result, it barely seems that fast short term improvement with mentioned 40% target is foreseeable.

As we will see in next sections, urgent completion of north-south lines is absolutely crucial in context of the whole region. "As long as the new power lines between north and south Germany are not completed, the problem of a lopsided system that requires frequent interference from grid operators will only worsen" (Appunn 2015).

[34]Nevertheless, this is estimated to be up to 5 times more expensive than ordinary lines. Kilometre of lines costs 1,2 Mio EUR whilst kilometre of cable costs 6 Mio EUR (Rapp 2012)

[35]One such recently finished example can be found in the Rheinlad-Westfalen federal state. (Source: http://www.welt.de/wirtschaft/energie/article146848975/Erdkabel-fuer-Strom-schaffen-viele-neue-Probleme.html)

[36]According to the opinion poll of Agentur für erneurbare Energien from August 2015, 93% of inhabitants support or strongly support Energiewende in general. Solar parks and wind plants in the surroundings are positively seen by 77% or 59% respectively (Agentur für erneubare Energien 2015)

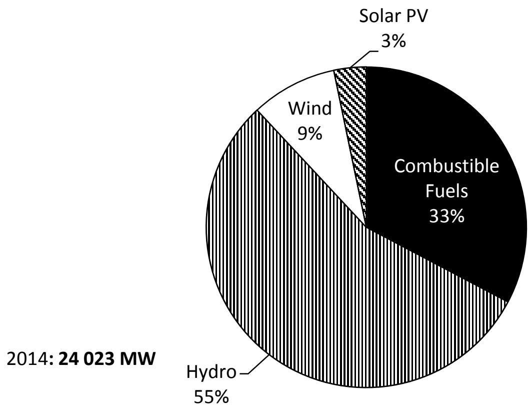
2.3 Power systems of remaining CE countries

2.3.1 Austria

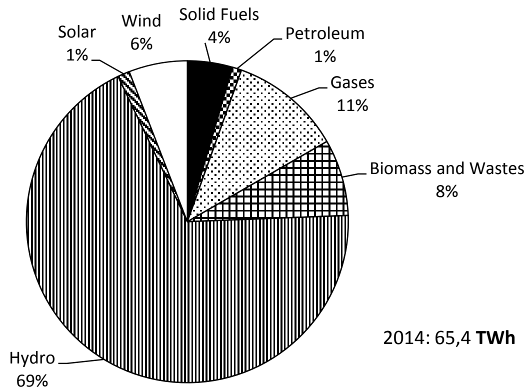
Current situation

With 83 % share of renewables on total electricity generation, Austria is a leading nation in CE in ecological production. This is given by the presence of the Alps on the Austrian territory which are very rich source of water energy. As can be seen in the figure 2.14, hydro power is thus a major contributor to the total renewable share.

Figure 2.14: Installed capacity and electricity generation in Austria



(a) Installed capacity as of 31.12.2014



(b) Electricity production by fuel type 2014

Source: European Commission, DG Energy (2016a)

It is important to note that majority of the hydro power plants' installed capacity exists in the form of pumped storage power plants (7969 MW). The remaining 5599 MW of hydro capacities are then ordninary run-of-river power plants (E-CONTROL 2016).

According to the data of European Commision, 65.4 TWh of electricity was generated in Austria. Regargind the balance, net import accounted for 9.275 TWh in 2014 which corresponded to 13.46% of 2014 inland consumption (European Commission, DG Energy 2016a; E-CONTROL 2016). This pattern can be moreover observed from the very long-term perspective[37]

Moving to the other renewables, especially wind and solar plants, 2871 MW of intermittent capacities were installed in 2014. This corresponded to 12% of

[37] The last year, when the courtry was net exporter of electricity, was in 2000 (European Commission, DG Energy 2016a)

total installed capacity. Historical overview and development of the renewable sources for remaining CE countries can be seen in the figure 2.4 below.

Table 2.4: Development of VRES in Austria, Slovakia and Poland

Country	Installed MW	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SK	Wind	0	0	0	3	3	5	5	5	5	3	3	3	3	5	3
	Solar	0	0	0	0	0	0	0	0	0	0	19	496	513	588	533
AT	Wind	50	67	109	322	581	778	935	968	988	994	981	1 080	1 316	1 645	2 086
	Solar	5	7	9	23	27	30	36	40	49	71	154	317	363	626	785
PL	Wind	4	19	32	35	40	121	172	306	526	709	1 108	1 800	2 564	3 429	3 836
	Solar	0	0	0	0	0	0	0	0	0	0	0	1	1	2	27
Source:	European Commission, DG Energy (2016a)															

Transmission network

Austrian transmission network, operated by the company APG, plays a key role in Central Europe as it is a crucial cross-road for transport of electricity form the Czech Republic and Germany to south-eastern European countries. The high-voltage transmission grid consists of 380 kV (2577 km), 220 kV (3212 km) and 110 KV (1182 km) of lines summing up to 6971 km. There are also 63 substations (APG 2016).

The responsibilities of APG are similar to previous TSOs and include transport coordination, grid operation management, load flow optimisation and congestion management as well as grid development. Especially a grid development is a current topic in Austria. In 2015, ten year Network development plan was approved which proposes grid reinforcement and expansion measures to meet the common challanges of European energy transition. These measures include upgrade of existing lines to higher voltage levels, construction of substation and transformers as well as 370 km of new transmission lines (APG 2015).

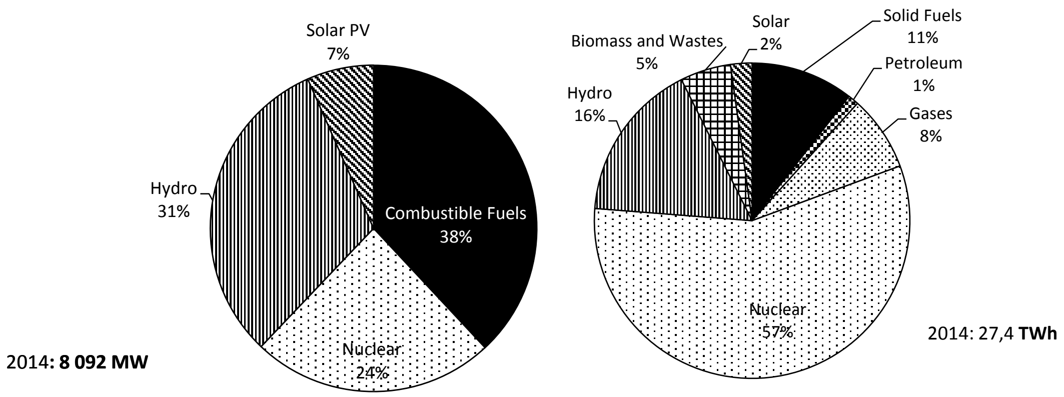
2.3.2 Slovakia

Current situation

Slovak production as well as consumption of electricity is the lowest in the region. According to European Commission, DG Energy, 27.4 TWh of electricity was produced in Slovakia from the power plants with installed capacity of 8092 MW. The greatest share (57%) came from nuclear power plants and hydro power plants (16%) which are situated mostly on coutry's greatest rivers (Danube, Váh). As well as the Austrian power system, Slovak system is typical of low share of fossil fuels on total electricity production (20%) (Fig. 2.15).

From the balance perspective, Slovakia is net electricity importer since 2006 when it had to shut down part of Jaslovské Bohunice nuclear power plant. In 2014, imports accounted for 1.1 TWh which represents 3.9% of consumption. The amount of imports between different years substantially varies (European Commission, DG Energy 2016a; Ministersvo hospodárstva Slovenkej republiky 2015).

Figure 2.15: Installed capacity and electricity generation in Slovakia



(a) Installed capacity as of 31.12.2014 (b) Electricity production by fuel type 2014

Source: European Commission, DG Energy (2016a)

Except hydro plants, renewable sources in Slovakia are centered around biomass, biogas and solar power plants. The installed capacity of wind power plants in negligible (3 MW in total of two wind parks in 2014). Exact overview and developmet is given in the table 2.4.

Transmission network

Likewise the Czech grid, Slovak transmission network was for a very long time part of common Czechoslovakian system which was developed together as one system. This explains the extraordinary good interconnection capacity of Slovak network, which reaches as high as 61% (2.5, and the absence of bottlenecks on the Czech-Slovak border.

It is also important to note that Slovak grid is important in the international context for the Czech Republic as exports to Slovakia are almost fully passed further on Hungary[38].

[38] In 2014, 9392 GWh of electricity was imported from the Czech Republic and 9356 was exported to Hungary (Ministersvo hospodárstva Slovenkej republiky 2015)

The high-voltage grid itself is mantained by the state owned company SEPS which acts as a Slovak TSO. It is responsible for 1953 km of 400 kV lines, 826 km of 220 kV lines, 80 km of 110 kV lines and 26 substations.

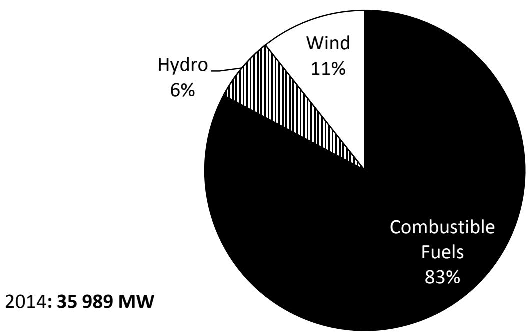
Also the Slovak grid will be subject to reinforcements and upgrades. In 2014, SEPS issued Ten year development plan for the years 2015-2024. In here, investments reaching 564 mil EUR are outlined. They concern mostly internal advancement of infrasturcture as well as expansion of cross-border transmission lines, particularly on Slovak-Hungarian borders. All other border profiles are not included in projected investment plans as their capacitiy is sufficient (SEPS 2014).

2.3.3 Poland

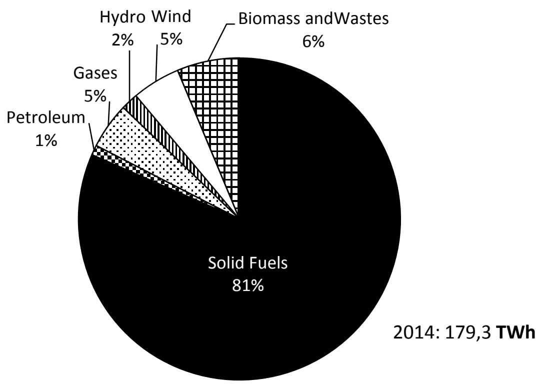
Current situation

Polish power system is characteristic by the reliance on coal power plants which are mostly feeded by home produced lignite and hard coal. Out of 179.3 TWh of electricity production, 81 % was generated by coal fired power plants in 2014. Hard coal power plants supplied 80.24 TWh and lignite power plants 54.2 TWh (PSE 2015c). Second most utilized source were then biomass and wind power plants (6% and 5% respectively). Detailed overview is given in the figure 2.16

Figure 2.16: Installed capacity and electricity generation in Poland



(a) Installed capacity as of 31.12.2014



(b) Electricity production by fuel type 2014

Source: European Commission, DG Energy (2016a)

Especially the wind power plant installed capacity growth was significant in past years which can be mainly attributed to the fact that Baltic sea and surrounding regions offer suitable conditios for wind production. Since 1998, it thus evinced almost exponential growth which slowed a bit in recent years. Nevertheless, we can still see almost 3.5 time increase between 2010 and 2014 (table 2.4)

Regarding the international balance, Poland is structurally electricity exporter. Nevertheless, in 2014 we can observe import of 2.16 TWh which accounted only for 1.36% of annual consumption for 2014 (PSE 2015c).

Transmission network

Polish high-voltage transmission network, whose operator is the company PSE, consists of 3 types of lines - 1 line of 750 kV (114 km), 89 lines of 400 kV (5984 km), 167 220 kV lines (7971 km) and 106 substations. There is also one DC connection in the form of undersea cable of 450 kV of 254 km (but only 127 km is mantained by PSE) (PSE 2015b).

Generally, Polish system suffers form very low denstity in northern areas as well as very low interconnection level of only 2% which entails severe problem when transmission of electricity is considered. Very often, congestion and hitting up of limits of the lines occur. The most critical situations appear on Polish-German border where only 4 interconnectors on the voltage level 220 kV are present.

Contemporary "Development Plan for meeting the current and future electricity demand for 2016-2025" takes this fully into account. The existing interconnectors are planned to be upgraded to 400 kV levels. Moreover, after the grid in western Poland is reinforced by 2020, new interconnector is projected after 2025. PSE also plans major infrastructure enhacment within whole Poland which is the precondition for successful connection of new expected power plant units, including mostly wind, gas and coal ones. Outlays in the first half of the period should account 6.98 bn PLN, in the second half then 6.28 bn PLN (PSE 2015a).

2.4 Transmission systems in the international context

As it was already sketched, transmission systems are mutually interconnected and it is thus not possible to conduct analysis only on the basis of a single country. For this reason, we work with the whole region of Central Europe, in particular with Germany, the Czech Republic, Poland, Slovakia and Austria[39]. As can be seen in the next chapters, even other states are later incorporated for the purposes of modeling.

2.4.1 Market design description and cooperation setup

Electricity market has one major feature in comparison to other commodity markets. Under current level of technology, possibilities of storing electricity are extremely limited as well as expensive. Hence, the condition of equality of supply and demand at particular time and place has to be satisfied. Various forms of electricity trading on long-term markets (forward), short-term markets (day-ahead, intraday markets) and balancing markets are used as a tool to assure the overall equilibrium. The results of this trading are called commercial or scheduled flows.

Nonetheless, it is important to have in mind that the nature of physical electricity flows does not have to, and actually mostly does not, correspond to the planned commercial flows. In fact, the flows are subject to physical laws which determine the flows based on current situation in the network.

The difference between the actual and scheduled flow of electricity is called an unplanned flow. Practically, they describe the deviation of expectations in form of traded contracts from the real flows of electricity. Maintenance of unplanned flows is the main task in securing safe functioning of the system with respect to the necessary condition of balancing demand and supply of electricity in the grid.

The responsibility for maintenance of stability is most frequently in hands of TSOs[40] who supervise their particular territory and monitor and manage cross-border electricity flows by the means of trade as well as by the means of physical controls, including congestion management[41] (Kunz 2013).

[39]To remind, Germany is divided into four TSO control zones Tenne-T, 50 Hertz, Amprion and TransnetBW. Austrian territory consists de facto from one control zone with the APG as TSO (www.apg.at). Polish TSO is the company PSE (www.pse.pl) and Slovak one is the company SEPS (www.seps.sk)

[40]In this thesis, all of TSOs in mentioned CE countries are legally obliged to assure such stability (Source: web pages of TSOs)

[41]Kunz (2013) gives following definition of congestion and congestion management: Congestion represents the situation when technical constraints (e.g. line current, thermal stability, voltage stability, etc.) or economic restrictions (e.g. priority feed-in, contract enforcement, etc.) are violated and thus restrict the power transmission between regions. Therefore, congestion management is aimed at obtaining a cost optimal power dispatch while accounting for those constraints

2.4.2 Cross-border problems and its precauses.

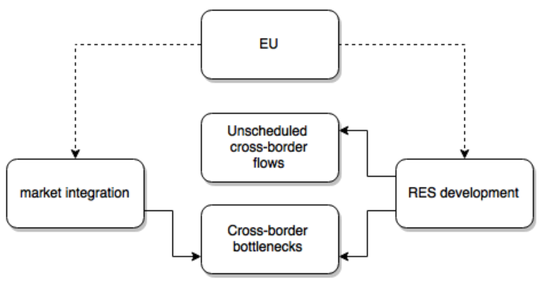
From the international perspective, electricity generation as well as transmission systems were historically maintained primarily on local, mostly national, level by domestic highly-controllable production. Trading was limited and cross-border transmission interactions took place only in case of emergency grid balancing. Transmission grid and power system infrastructure reflected this setup fully throughout Europe.

However, real efforts of integrating the European electricity market into one area as well as promoting renewable energy led to a transition that came in 1996 and afterwards. In this time, three legislative packages and other legislature were passed by the European parliament aiming to the transparency, regulation, consumer protection and overall integration.

These packages, combined with the packages on promotion of renewable policies, started to change the structure of European energetics completely without having considered the side-effects of these policies on cross-border congestion, volatility and unpredictability of VRES production resulting from such setup.

These concerns are confirmed also by IEA publication on EU energy policy which states following: "The investment and large-scale additions of variable non-dispatchable renewable energies in Central and South Europe have brought about a number of new challenges for the wholesale electricity markets, the merit-order dispatch, system operation and grid management, as electricity trade flows across borders and at the distribution network level increased" (IEA 2014). Simplified graphical interpretation of problems can be seen in the figure 2.17 below.

Figure 2.17: Cause and effect diagram



Source: Author

Eventually, to illustrate briefly the interconnections problems in more depth, we can have a look on interregional interconnection level. Even though 10% interconnection level was set in 2002 and reassessed in 2014 to reach 15% by 2030, it is quite clear that with increasing amount of trade and growing production from VRES, such target is insufficient. According to IEA, the capacity should be increased by at least 40% (IEA 2014). Interconnector levels for the year 2014 are shown in the table 2.5.

Table 2.5: Interconnection levels in CE

Country	Austria	Czech Republic	Germany	Poland	Slovakia
Interconnection level (2014)	29%	17%	11%	2%	61%
Source:	European Commission (2014b)				

2.4.3 CE context

In the context of Central European region, all the aforementioned is represented by following issues:

- Grid bottlenecks between southern and northern Germany
- Energiewende - Unprecedented growth of VRES production and nuclear phaseout
- Market setup: German-Austiran electricity bidding zone

First two factors were thoroughly examined in previous sections from national perspective; now we will pay attention to the last point, German-Austrian bidding zone.

DE-AT Bidding zone

Generally, according to ENTSOE definition, "Bidding zones are network areas within which market participants can offer energy - in the day ahead, intraday and longer-term market time frames - without having to acquire transmission capacity to conclude their trades"[42] (ENTSOE n.a.). Management of such zone is then the responsibility of TSOs which have to assure that there is no congestion inside the bidding zone and participants can trade without restrictions.

[42] In other words, this means that any subject is allowed to contract power without limitations and hence disregarding the physical reality of the transmission network

With respect to what was said about the shape of the infrastructure, bidding zones are frequently set to correspond to national borders, even though there are some exceptions within EU[43]. Setting up a bidding zone has several advantages as well as disadvantages. Main benefits are the equality of the price of wholesale electricity in the bidding zone, higher effectivity and transparency of the market and mentioned implicit capacity allocation (ACER 2015). This is based on the fundamental assumption of sufficient transmission capacity within bidding zone. The main drawback is that the internal flows in a huge bidding zone cannot be controlled which implies that the flows also have an impact on adjacent bidding areas (ČEPS *et al.* 2012). Usual reaction of responsible TSO's is decline of cross-zonal tradable transmission capacity[44]. As such, proper bidding zone delineation is critical for efficient functioning of the system; otherwise, such zone can represent hindrances in the electricity market.

Austria and Germany are one of the single-country bidding zone exemptions and form a major bidding zone in Central Europe where the common electricity prices and unrestricted trading are enjoyed. Nevertheless, this area suffers severely from the drawbacks described above. Firstly, insufficient internal transmission capacities prevent the zone setup to deliver more efficient structure than the original one. Secondly, significant negative overflows are imposed on neighbouring countries.

Impact of changes in market setups are not assessed in this thesis. Nonetheless, the debate about this issue is still very lively and heated. This can be illustrated on the recent case from the end of September 2015. After several years of common effort of Czech, Slovak, Polish and Hungarian TSOs, the Agency for the Cooperation of Energy Regulators (ACER) took a position, though legally unbinding, that the "exclusion of the common bidding zone of Germany and Austria from the coordinated cross-border capacity calculation procedure in the Central Eastern Europe (CEE) is not in line with EU rules and should be terminated" as "the current regime at the German-Austrian border accounted for congestion in neighboring transmission grids" ČEPS (2015a).

This could be seen as a break-through in protracted negotiations. By many,

[43]For example, Sweden and Italy are divided into several zones whereas Germany and Austria form one bidding zone (ACER 2015)

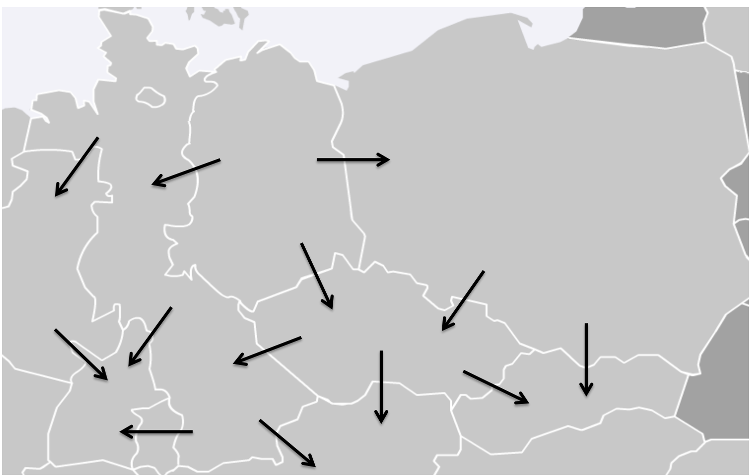
[44]We refer here to Net Transfer capacity (NTC) which is main determinant of free cross-border commercial transmission capacities between particular zones. Exact definition gives us: "Net Transfer Capacity is the maximum capacity for exchange of power between two areas, compatible with security standards applicable in both areas and taking into account the technical uncertainties on future network conditions" (PSE 2016)

it was expected that this document will become the basis for the actual zone splitting. Nevertheless, in January 2016, Director of DG Energy in European Commission Mechthild Wörsdörfer declared, that European Commision is against the split of the biding zone as it considers this step to be "meaningless" (Kamparth 2016) and supported thus the stance of the Austrian regulator E-control. With high degree of certainty, the final outcome will be reached rather in a very long term, if at all.

Bottlenecks and loop flows

The international dimension of this problem is represented by the fact that, in accordance with the physical nature of electricity, in the absence of particular capacities, electricity flows through free capacity in the grid elsewhere which creates unscheduled flows affecting all neighbouring countries (predominantly the Czech Republic and Poland). In here, several problems in national transmission grids are caused (Mišík 2015). These unplanned power flows can be split into external flows created by internal commercial transactions in one country (traditionally called "loop flows") and external power flows created by commercial transactions between two countries (traditionally called "transit flows") (ČEPS *et al.* 2012). In CEE context, especially loop flows exemplify substantial threat to the stability of the grid as these flows over particular interconnections are mostly unplanned and are thus unexpected by the TSO. Unpredictable production from VRES, mainly wind parks, is main determinant of these flows as this production is gusty both in amount and time (ČEPS 2010a).

Figure 2.18: Structure of flows in CE



Source: Own, based on ENTSOE (2016a) maps

Chapter 3

Literature review

Modeling of power systems or electricity markets differs from the pure economic or financial models to a large extent. The reasoning is hidden in the necessity to account for the underlying technical characteristics and limitations of the production assets specific to electricity (Ventosa *et al.* 2005).

In the last decades, modeling of the European electricity markets experienced significant upswing both in quality and quantity of the models. This goes in hand with EU policies taking gradual steps to demonopolize, decentralize and unbundle the energy markets, especially the one for electricity (Leuthold *et al.* 2012).

3.1 Modeling approaches

Each model abstracts from a reality to a certain degree as it uses stylized facts, simplified figures, past trends as well as other assumptions. Herbst *et al.* (2012) notes:

> "Energy models represent a more or less simplified picture of the real energy system and the real economy; at best they provide a good approximation of today's reality. Nevertheless, it would be impossible to answer very specific questions on energy technologies or economic implications without making some cut backs and approximations"

Trends in electricity market modeling are very various depending on the target group, intended use, regional coverage, conceptual framework and many other factors (Herbst *et al.* 2012). This implies that there is an abundance of model clusters with no unified division. Few approaches are presented here based on the above mentioned criterions. Moreover, model employed in this thesis is put into their context.

Optimization, Equilibrium and Simulation models

Based on the works of Smeers (1997), Kahn (1998), Hobbs (2001) and Day *et al.* (2002), Ventosa *et al.* (2005) identifies three major trends in electricity market modeling. He speaks about optimization models, equilibrium models and simulation models.

Optimization models focus on the profit maximization of one particular company. Nontheless, this approach is not frequently used any more as there are basically no vertically-integrated compnaies in the liberalized electricity markets. In these models, optimized profit can be derived on the basis of the prices entering the model as an external parameter or via a function of the demand supplied by the firm.

On the contrary, equilibrium models take into account overall market behavior and consider competition among all participants (Ventosa *et al.* 2005). The market equilibrium is built on the concept of Nash equilibria, but depends on strategies of the players. Two kinds of them are feasible - Cournot competition, where firms compete in quantity, or the supply function equilibrium approach (SFE),where the firms compete both in quantity and price (offer curve strategies) (Ventosa *et al.* 2005).

Equilibrium models are generally very demanding to solve. When the degree of complexity is to large, simulation models can be considered as an alternative. Ventosa *et al.* (2005) describes simulation models as models which "typically represent each agent's strategic decision dynamics by a set of sequential rules". In applicaion, models closely related to the equilibrim models or agent based model are used.

Perfect vs. imperfect competition models

Unlike the previous approach, which deals mostly with the assumption of imperfect competition, Smeers (1997) took a look at the division of models according to the type of competition in the market. It is clear that perfect competition models are much more simple than the imperfect ones. The cost of simplification is the vulnerability to critique as it is evident that perfect competition assumptions do not reflect the real structure of the liberalized energy markets.

Despite this fact, Smeers (1997) suggests that the perfect competition models can be useful since they can handle large volumes of data. Moreover, imperfect market characteristics can be introduced into these models as well by taking quantitative restrictions or mark-ups into consideration(Smeers 1997).

Top-down vs. bottom-up models

Herbst *et al.* (2012) introduces another way of division of the models. He examines the conceptual framework and introduces the scheme of top-down and bottom-up models.

Top-down models tend to be developed and used by economists and public authorities. They try to depict the reality on the national or regional level by aggregating the energy systems. Herein, economic growth, price trends, demographic development and macroeconomic approach to the consumer welfare play an important role. Regulatory policies, emission trading schemes, environmental taxes or surcharges (e.g. feed-in-taffifs) are mostly evaluated on the basis of this models (Herbst *et al.* 2012). Input-Otput models (Catenazzi 2009), econometric models (Cambridge Econometrics 2011, E3ME), computable general equilibrium models (Bernard & Vielle 2008, GEMINI-E3) and system dynamics models (Krail & Schade 2010, ASTRA) are the best representatives of this approach.

On the contrary, bottom-up models are constructed and employed in the works of engineers, natural scientists, and energy supply companies as they are aimed at technological focus and developmnent, system explicitness and business oriented aproach. This enables them to deliver very detailed pictures of energy demand and energy supply technologies, technology futures or investment, costs, and benefits of energy efficiency measures (Herbst *et al.* 2012). Partial equilibrium (POLES, WEM, PRIMES), optimization (MARKAL, TIMES), simulation (LEAP, BUENAS, PAMS) and multi-agent based models (Möst & Genoese 2009; Sensfuss *et al.* 2008) are the most frequent types.

In the last decade, efforts were made to merge the bottom-up and top-down approach to one hybrid energy system models (Rivers & Jaccard 2005; Hourcade *et al.* 2006; Böhringer & Rutherford 2008; Labriet *et al.* 2015)

3.2 ELMOD model

In this thesis, the fully overtaken state-of-the art version of European ELMOD[1] model was employed. As it will be seen in next paragraphs, the reason for choosing this model is connected to a high degree of technical detail which makes it the best choice when considering transmission system or load flow analysis. This statement is then also supproted by existing similar research for which this model was used (see section 3.3).

Several research institutions from Germany took part in bulding and enhancing this model. It was initialized at the Dresden University of technology by Leuthold *et al.* (2008). Continuous improvement has been taking place at the Chair of Energy Economics at TU Dresden, the Department for Energy, Transportation, Environment (DIW Berlin), the Workgroup for Infrastructure Policy (TU Berlin) and the Energy Economics Department (University of Basel) (Egerer 2016).

In the context of previous literature review, ELMOD model can be classified as a large scale non-linear bottom-up optimization model maximizing general social welfare fucntion under production and transmission constraints and under the assumption of perfect competition among market players. Also, an independent system operator, optimizing the system variables for the entire regional scope of the model, is assumed (Kunz 2013). As the bottom-up approach indicates, one of the biggest assets of this model is the high degree of technical introspection, in particular the control for physical peculiarities of electricity as a commodity (Leuthold *et al.* 2012).

These peculiarities can be summarized by following. Hirth (2015) compares electricity to a "arechetype of commodity". It is traded via standardized contracts and it is perfectly homogeneous good at one time, space and lead-time of delivery. However, physical laws imply significant constraints with economic implications (Hirth 2015).

Firstly, large scale storage is impossible provided currently feasible technologies are taken into acount[2]. Thus, electricity supply and demand are required to be in equilibrium in each time period to secure properly operating system.

Secondly, electricity is transported by transmission networks, a specific network systems, which is subject to capacity and thermal restrictions, security

[1] It is open source model which cas be accessed here: http://www.diw.de/elmod

[2] The only exception that allows for storing electricity in the form of water potential are pumper storage power plants. These are subject to a special treatment as desrcibed in the section 4.1

constraints and physical laws (Kirchhoff and Ohm laws) determining the flows on particular lines in the meshed network.

Whole model was coded and solved in GAMS (General Algebraic Modelling System) software. Due to the non-linear nature of the model, GAMS CONOPT module was crucial for solving it.

3.3 Applications of ELMOD and energy modeling in CE

Since the publication of the model in Leuthold *et al.* (2008), many research works applied the model. ELMOD is most frequently used for analysis of market design (Neuhoff *et al.* (2013); Egerer *et al.* (2015)), influence of renewables on transmission networks (Egerer *et al.* (2009); Schroeder *et al.* (2013)) including grid and power plant investment decisions (Leuthold *et al.* (2009); Weigt *et al.* (2010); Dietrich *et al.* (2010); Egerer *et al.* (2013)), uncertainty and stochastic effects (Abrell & Kunz (2012)) and congestion management issues (Kunz (2013); Kunz & Zerrahn (2015; 2016)).

If we focus on particular literature on energy modeling in the region of CE, we can divide it in two groups. The first one is more extensive and examines renewables most frequently on country level. The second one then concerns transmission networks.

Among the above mentioned ELMOD literature focused primarily on Germany, other German renewable-related studies include investigation of hydro pump-storage power plant (Steffen 2012; Schill & Kemfert 2011), renewable surplus and residual load (Schill 2014), discussion about the sustainability of energy transition (Hinrichs-Rahlwes 2013), assessment of its successfulness (Pegels & Lütkenhorst 2014) and costs (McKenna *et al.* 2014; Wand & Leuthold 2011) as well as discussions about market design etc. (Trepper *et al.* 2015; Stötzer *et al.* 2015; de Menezes & Houllier 2015)

Renewables literature in the Czech Republic focused on meeting the EU renewable targets (Sivek *et al.* 2012), quantifying the costs of renewables (Janda *et al.* 2014; Průša *et al.* 2013) and green investment schemes (Karásek & Pavlica 2016). The papers of Rečka & Ščasný (2016; 2013) go even beyond the scope of renewables and model the Czech energy system as a whole.

Austrian research in renewables studied the questions linked to potential of wind (Gass *et al.* 2013), efficiency of bioenergy technologies (Kalt & Kranzl

2011) or assessment of national renewable energy scenarios (Madlener *et al.* 2007) and effect of renewables on prices in German-Austrian zone (Würzburg *et al.* 2013).

Slovak researchers concentrated on photovoltaics development (Šály *et al.* 2006) and interchangeability of nuclear and renewable power sources (Lofstedt 2008).

Polish academicians conducted freuquently research in the fields of the potential of renewables in general (Paska & Surma 2014) as well as on individual-technology level of bioenergy (Chodkowska-Miszczuk & Szymańska 2013; Igliński *et al.* 2011) and wind (Brzezińska-Rawa & Goździewicz-Biechońska 2014). Likewise, local possibilities of renewable production (Juroszek & Kudelko 2016; Igliński *et al.* 2016; Piotrowska-Woroniak *et al.* 2015) and impact of EU goals on electro-energetic mix (Gawlik *et al.* 2015) were investigated.

Literature on transmission networks and grid in CE is a bit less extensive. Apart from mentioned ELMOD literature, we can find several other articles which mostly deal with optimal grid extension or integration of renewables into the grids. Nevertheless, these have a look on Germany (Winkler *et al.* 2016; Singh *et al.* 2015) or Europe as a whole (Fürsch *et al.* 2013; Majchrzak *et al.* 2013; Schaber *et al.* 2012a;b). Grid related literature in Poland examined most often possibilities of phase-shifting transformers (Korab & Owczarek 2016; Kocot *et al.* 2013).

The literature paying pure attention to the region of CE is very sparse. Few examples are very recent articels from Singh *et al.* (2016), analysing the impact of unplanned power flows on transmission networks, Eser *et al.* (2015), assessing the impact of increased renewable penetration under network development and Kunz & Zerrahn (2016) focusing on cross-border congestion management.

Chapter 4

The model

4.1 Model formulation

Various forms of ELMOD can be emloyed depending on the research question's objective. In this thesis, model specified in Leuthold *et al.* (2008) was used as a basis with some further restrictions relating to the direct-current load flow nature. These can be found in Leuthold *et al.* (2012) and Egerer *et al.* (2014).

4.1.1 Model notation

Sets and indices:

L	set of all lines
N	set of all nodes
C	set of all conventional plants
T	set of all time periods
$l \in L$	line within the network
$n, nn \in N$	nodes within the network
$n' \in N$	slack node(s) within the network
$c \in C$	conventional power plant unit
$t \in T$	time periods

Parameters:

G_{nt}^{wind}	Wind input at node n in time t
G_{nt}^{solar}	Solar input at node n in time t
PSP_{nt}^{out}	Pump storage plant release at node n in time t
PSP_{nt}^{in}	pump storage loading at node n in time t
G_{ct}^{max}	maximal generation of generation unit c in time t

$\overline{P}_{lt}$	maximal available capacity limit of line l in time t
H_{ln}	network transfer matrix
$B_{n,nn}$	network susceptance matrix
A_{nt}	intercept coefficient at node n in time t
D_{nt}	slope coefficient at node n in time t
M_{nc}	marginal cost coefficient of power plant unit c at node n

Variables:

w	welfare function
$\pi_{nt}(q_{nt})$	inverse demand function at node n in time t
$m_{nct}(g_{nct})$	marginal cost of generation of plant c at node n in time t
g_{nct}	generation of generation unit c at node n in time t
q_{nt}	demand at node n in time t
ν_{nt}	net input to node n in time t
p_{lt}	power flow over line l in time t
$\theta_{nt}, \theta_{nn,t}, \theta_{n't}$	flow angle at node n in time t

4.1.2 Model form

$$\max_{g,q} \quad \sum_T \sum_N \Big((A_{nt}q_{nt} + \frac{1}{2}D_{nt}q_{nt}^2) - \sum_C g_{nct}M_{nc} \Big) \tag{4.1}$$

$$s.t.$$

$$\sum_c g_{nct} + G_{nt}^{wind} + G_{nt}^{solar} + PSP_{nt}^{out} - PSP_{nt}^{in} + \sum_{nn} \theta_{nn,t}B_{n,nn} - q_{nt} = 0 \quad \forall n,t \tag{4.2}$$

$$g_{nct} \leq G_{ct}^{max} \quad \forall n,c,t \tag{4.3}$$

$$p_{lt} = \sum_n H_{ln}\theta_{nt} \quad \forall l,t \tag{4.4}$$

$$|p_{lt}| \leq \overline{P}_l \quad \forall l,t \tag{4.5}$$

$$\theta_{n't} = 0 \quad \forall n,t \tag{4.6}$$

4.2 Model description

4.2.1 Welfare function

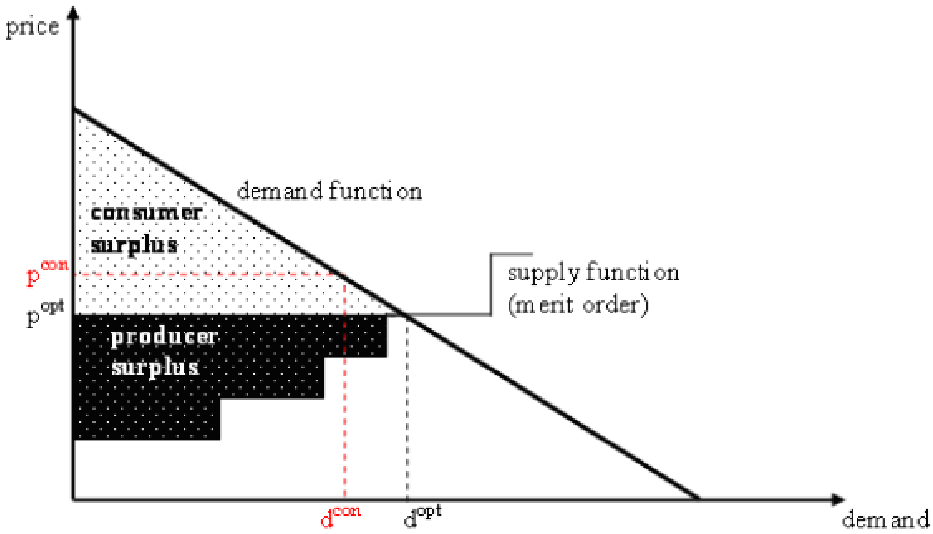
The objective function in the ELMOD model is a social welfare function which is maximized after taking into account the technical and physical peculiarities connected to electricity. In the model, these include energy balance (4.2), generation constraint (4.3) and line flow restrictions (4.4)-(4.6).

The general form of the ELMOD social welfare function was formulated in Leuthold *et al.* (2008). It has the form of:

$$w(g,q) = \sum_{n,t} \Big(\int_0^{q^*_{nt}} \pi_{nt}(q_{nt}) dq_{nt} - \sum_c g_{nct} m_{nct}(g_{nct}) \Big) \tag{4.7}$$

Welfare is thus obtained by subtracting the generation cost[1] form the area below the demand curve. In other words, we are left with sum of the producer and consumer surpluses. Graphical illustration is provided in the figure 4.1.

Figure 4.1: Welfare in the electricity market



Source: Leuthold *et al.* (2008)

General inverse demand function of the form $\pi_{nt}(q_{nt})$ and general supply function of the form $g_{nct}m_{nct}(g_{nct})$ are used in (4.7). Nevertheles, **linear** functions are assumed most frequently in ELMOD. Such simplification is also employed in this thesis.

[1]These cost are composed of the amount of generation and marginal cost of each unit's generation

Simirarly to the application of Leuthold *et al.* (2012), the linear inverse demand function has the form of:

$$\pi_{nt}(q_{nt}) = A_{nt} + D_{nt}q_{nt} \tag{4.8}$$

where A_{nt} is nonnegative intercept and D_{nt} is negative slope coefficient which are used to estimate the demand function. Exact derivation is given in the Appendix A.

Supply function is also linearized. The marginal cost function $m_{nct}(g_{nct})$ is replaced by the coefficient M_{nc} determining the time-invariant marginal cost of generation for each individual power plant unit c at node n based on the model data[2].

If we want to derive the welfare at node n and time t using linear functions, we need to calculate the area below the demand function and below the supply function and subtract them. Area below inverse linear demand function (4.8) is determined followingly:

$$\int (A_{nt} + D_{nt}q_{nt})dq_{nt} = A_{nt}q_{nt} + \frac{1}{2}D_{nt}q_{nt}^2 \tag{4.9}$$

The right-hand side leaves us exactly with the term that is used in the first part of the objective function (4.1). Area below the supply fuction is the sum of generation costs of all power plant units at node n and time t:

$$\sum_c g_{nct}M_{nc} \tag{4.10}$$

If (4.9) and (4.10) are subtracted and the result is summed up over all nodes and all time periods, objective function (4.1) is obtained. It is important to say that this function is concave. This follows form the fact that coefficients A_{nt} and M_{nc} at linear terms are positive for all n and t and the coefficient D_{nt} at quadratic term is negative for all n and t.

4.2.2 Energy balance

As stated earlier, ELMOD takes into account electricity specific restrictions. One of these is the criterion of balanced supply and demand which is captured by the equation (4.2). The equation includes all electricity inputs and sets

[2]The calculation of M_{nc} for particular power plant consists of definition of power plant technology, fuel price, fuel carbon content,carbon price and power plant efficiency. Exact formula is given in the Appendix A

them equal to the withdrawals from grid and net inputs. Electricity inputs include total generation from conventional power plants $\sum_c g_{nct}$, wind generation G_{nt}^{wind}, solar generation G_{nt}^{solar} and storage power plant release PSP_{nt}^{out}[3]. Grid withdrawals are repsented by nodal demand q_{nt} and consumption of pump-storage power plants for pumping PSP_{nt}^{in}. The remaining term, net input $\sum_{nn} \theta_{nn,t} B_{n,nn}$ labeled by ν_{nt} in the model notation, is important ELMOD - specific feature and defines whether electricity is injected or withdrawn from the grid at respective node (Leuthold *et al.* 2008). The nature of net input is closely tied to physical power flows constraints and constitutes actually a system power imbalance (Expósito *et al.* 2004).

4.2.3 Network constraints and flow model

Remaining equations from (4.3) to (4.6) impose other physical - based restrictions and define how power flows are modeled.

First limitation in the form of inequality (4.3) states that the electricity production from power plant is bounded by the installed capacity of given production unit and cannot exceed this value[4]. Inequality (4.5) take into account the capacity limits of individual transmission lines and restrict the modeled flow to respect these upper and lower values respectively. Moreover, the parameter on maximum limit inherently incorporates the system security criterion by allowing for some reliability margin at each line. Closer details on security assumptions can be found in the section 4.3.2.

Equations (4.4) and (4.6) are central to the model. Equation (4.4) models the flow over particular line in a given time and the equation (4.6) sets the phase angle for an arbitrary slack node to zero to ensure the uniqueness of solutions[5] (Egerer *et al.* 2014). The term ν_{nt} representing the net input variable cannot be also ommited. Due to the importance of these three features, deeper insight and more extensive commentary will be provided.

[3]In this model, wind, solar and PSP release or loading are treated as external parametres

[4]It implicitly follows from the definition that the production cannot be negative

[5]The terms net input and slack node are explained in the part "Net input & Slack node" of this section. Definition of voltage angle is following: "When capacitors or inductors are involved in an AC circuit, the current and voltage do not peak at the same time. The fraction of a period difference between the peaks expressed in degrees is said to be the phase difference" (Georgia State University 2016)

Power flow

Static power analysis has been subject to many research questions and, as such, power flow modeling is very established discipline in the field of electrical engineering.

Formulation of electricity model requires four basic variables at each system node i which include active power [6] injections P_i, reactive power[7] injections Q_i, voltage angle θ_i and voltage magnitude U_i. Such setup is known as AC load flow model.

For model solution, two variables must be known in advance at each node. This formulation results than in non-linear system of equations requiring iterative solution methods which are generally computationaly very demanding (Seifi & Sepasian 2011).

With regard to respective physical rules and laws, active and reactive power flows on particular lines can be computated based on series conductance[8] G_{jk}, series susceptance[9,10] B_{jk}, voltage angle differences θ_{jk} and voltage magnitudes U_j and U_k. Detailed general derivation can be found in Seifi & Sepasian (2011) and derivation applied in this thesis can be found in Stigler & Todem (2005). The resulting equations for active and reactive powers over line between the nodes j and k are following:

$$P_{jk} = G_{jk}|U_j|^2 - G_{jk}|U_j||U_k|\cos\theta_{jk} - B_{jk}|U_j||U_k|\sin\theta_{jk} \tag{4.11}$$

$$Q_{jk} = -B_{jk}|U_j|^2 - B_{jk}|U_j||U_k|\cos\theta_{jk} - G_{jk}|U_j||U_k|\sin\theta_{jk} - \frac{1}{2}B_{jk}^{sh}|U_j|^2 \tag{4.12}$$

As a result of immense computational difficulty, simplified models are very frequently used in economic applications. Very common simplification of AC load flow is DC load flow model (DCLF) which allows for linearization at the cost of some restrictive assumptions causing lower level of accuracy[11].

[6] Active power is the power drawn by the electrical resistance of a system doing useful work

[7] Reactive power is the power stored in and discharged by the inductive motors, transformers or solenoids

[8] Conductance is the real part of admittance which measures the ease with which an electric current passes through a component

[9] Susceptance is the imaginary part of admittance

[10] Based on Stigler & Todem (2005), conductance and susceptance can be calculated using these formulas $G_{jk} = \frac{r_{jk}}{r_{jk}^2 + x_{jk}^2}$ and $B_{jk} = \frac{x_{jk}}{r_{jk}^2 + x_{jk}^2}$ where r_{jk} stands for series resistance (the difficulty to pass electric current through a conductor) and x_{jk} for series reactance (the measure of opposition to the change in the current in AC circuit). Both these parametres enter the model as fixed values for respective voltage levels

[11] Overbye *et al.* (2004) discusses the actual differences between the AC and DC flow

ELMOD model follows the work of Schweppe *et al.* (1988) and Stigler & Todem (2005) where following assumptions are made to simplify the flow calculations:

- Reactive power (i.e. equation 4.12) flows are neglected
- Transmission lines losses are neglected
- Angle differences are assumed to be small
- Voltages are standardized to per unit levels[12]

Schweppe *et al.* (1988) shows how the assumption allow for mathematical simplification of equation (4.11). As a result of the procedure, DC load flow deals only with two variables - voltage angle and active power injections. The formula for power flow is thus reduced to

$$P_{jk} = B_{jk}\theta_{jk} \tag{4.13}$$

Last steps in obtaining desired result in form of particular line flow incorporate the identification of nodes *n,nn* and mapping to the lines. For this purpose, Leuthold *et al.* (2012) uses a special matrix, incidence matrix I_{ln}, which is defined followingly:

$$I_{ln} = \begin{cases} 1 & \text{if } n = j \\ -1 & \text{if } n = k \\ 0 & \text{else} \end{cases}$$

With the help of series line susceptance B_{ln}, final line power flow (4.4) can be obtained:

$$H_{ln} = B_{ln}I_{ln} \tag{4.14}$$

$$p_{lt} = \sum_{n} H_{ln}\theta_{nt}$$

Net input & Slack node

Referring to the previous text on net input, tehcnical description is added. Net input variable is determined by network susceptance matrix and voltage angles

applications. A conlusion is met that the loss of accuracy is very small and that DC results match pretty well AC load flow solutions provided the assumption of such simplification are met

[12]Nice discussion of applicability of these assumptions can be found in Purchala *et al.* (2005)

$\nu_{nt} = \sum_{nn} B_{n,nn}\theta_{nn,t}$. Mathematical derivation of the first parameter, the susceptance matrix $B_{n,nn}$, is based strongly on above mentioned flow definitions (Leuthold *et al.* 2012).

$$B_{n,nn} = \sum_{l} I_{ln} H_{ln} \tag{4.15}$$

This paragraph should shed light on the last equation of the model, equation (4.6). The equation sets the volatage angle of an arbitrary node, called slack node, to be zero which is important because uniqueness of solution of the system is thus guaranteed. Due to the setting of the voltage angle of one variable, all other angle values are relative to this specific one.

Slack node is closely tied to the net input, certain representative of system power imbalance. Slack node plays an important role here as real power generation from this particular node can be rescheduled to supply the difference between total system load plus losses and the sum of active powers specified at generation buses (Expósito *et al.* 2004). System-wide balance is secured as the individial net inputs sum up to zero in the whole system (Leuthold *et al.* 2012).

The decision about the slack bus is not important and can be completely random in models with enough buses. Nevertheless, Expósito *et al.* (2004) suggests to chose as a slack node the largest generator in the network. Such approach was also chosen in this application.

4.3 Data description

4.3.1 Datasets and data issues

Generally, gathering the data for the network model was not easy as no data with sufficient depth are publicly available from majority of official authorities in continental Europe due to security or economic sensitivity reasons (Egerer *et al.* 2014). In the region of CE and neighbouring countries, only German and Austrian TSOs provide publicly available information about the technical parameters of the transmission grid.

Regarding other countries, the only possible data source was to focus on the European network of transmission system operators (ENTSOE) which aggregates some information about network and electricity data from national operators. Nevertheless, in the current dataset provided by ENTSOE study model

(STUM) (ENTSOE 2016b), only coded, incomprehensible and non-replicable information about the grid was found as a result of data confidentiality.

Moving to the conventional thermal sources and hydro power plants, data accessibility is worse than in the previous case. Form the region in question, only German network agency, Bundesnetzagentur, publishes the complete list of operating power stations.

The only non-problematic dataset with enough information relates to the load and production data which are publicly disclosed under the "Electricity market transparency" scheme, the result of EU Regulation no 543/2013[13]. ENTSOE Transparency Platform aggregates all data.

Development of many models and datasets by researchers was the consequence of missing appropriate data. The community at the German Institute for Economic Research (DIW) did exactly this and published data and data documentation for electricity generation, load data, the high-voltage transmission infrastructure and price data in the paper "Electricity Sector Data for Policy-Relevant Modelling - Data Documentation and Applications to the German and European Electricity Markets" written by Egerer *et al.* (2014).

This thesis emloyed mentioned dataset but added several adjustments. Due to the bad accessibility of data, transmission network system, power plant units and their technical charasterisics were completely overtaken and resemble thus the state of the year 2012. Similarly to the application of Kunz & Zerrahn (2016), the rest of the dataset related to electricity was updated to reflect more current period, in our particular case the year 2015[14]. Thus, data for load, solar, wind, pump-storage plant generation and pump-storage plant pumping were obtained from the ENTSOE Transparency platfrom (ENTSOE 2016a) or from the pages of individual TSOs in case of unavailability in the Transparency platform. Data for the prices of electricity to calculate demand were obtained from the Quarterly Report on European Electricity Markets (European Commission, DG Energy 2016c). Data on power plant fuels were collected from several resources as shown in the table 4.1. Prices of CO_2 allowances were retreived from the database of European Energy Exchange (EEX) in Leipzig. Lastly, data on cross-country price differentions in gas and oil were collected from the Quarterly reports on European gas markets (European Commission,

[13]http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R0543

[14]This is an importnant contribution of the work. When working with the renewables data, it is very important to have the most updated generation data as these vary accross years due to a significant construction activity in countries of interest, especially Germany

DG Energy 2016d) and dabase of EU Crude Oil Imports and supply cost (European Commission, DG Energy 2016b).

4.3.2 Grid

The underlying grid data consist of nodes (transformer stations) which are connected by transmission lines (individual circuits). In several cases, auxiliary nodes are added on the intersection of lines. (Egerer *et al.* 2014). The dataset consists of 593 nodes, 10 country-specific nodes and 981 lines.

Each transmission line is characterized by several parameters necessary for conduction of a DC load flow model - number of circuits, length, resistance, reactance, voltage level and thermal limit. Details on the derivation as well as the assumptions can be found in chapter 4.2.3.

There are two levels of detail in the data. This thesis focuses primarily on the region of Germany, Czech Republic, Slovak Republic, Poland and Austria[15] and, as such, attempts to reflect the transmission system of these countries to a most possible level of detail. In particular, this means that structural nature of the network is modeled by taking into account actual lines and substations which are operated by the TSOs. Exact form of the transmission system can be found in Egerer *et al.* (2014, p.56). The second level is more aggregate. Following the idea of Leuthold (2009), adjacent countries[16] are represented by country-specific single nodes which are interconnected with the CE region as well as between each other. By the approach, the number and properties of interconnectors between the countries are unaffected.

These are important feature of the model for two reasons. First of all, it distinguishes the thesis from most of the research works which focuse primarily on Germany and model only German network in such a detail. After that, the aggregation of lines applied to the neighbouring countries of the region prevents the occurence of severe bias in resulting flows as a consequence of absent transit and loop flows of electricity between CE and adjacent areas. The transit can be illustrated on Italy, the biggest importer of electricity in Europe. Italy has terrestrial interconnections to France, Switzerland, Austria and Slovenia which supply or transport all the imported electricity[17]. If the connections to Italy

[15] To be referred to as "CE region"

[16] These countries consider all states which have interconnections to the CE region. The list is following: Netherlands, Luxembourg, France, Switzerland, Italy, Slovenia, Hungary, Denmark, Sweden

[17] 43 716 GWh in 2014

were ignored, transport would not take place in the networks which would bias the exchanges on all border profiles of the Italian neighbours[18]

The final dimension of the grid data regards security which the TSO has to take into account. In real life, this is captured by the "N-1" security criterion which is a basic criterion of power system stability. It requires that the system is able to operate and supply electricity provided a sudden outage of one system element occurs (Neuhoff *et al.* 2005). In the model, this security constraint is introduced by a 20% reliability margin in the thermal limit of each line (Leuthold *et al.* 2008, p.13).

4.3.3 Generation

Based on the approach in Egerer *et al.* (2014), generation capacities are divided between conventional and renewable sources which are treated accordingly.

Conventional

For conventional generation, individual units or power plants are considered separately [19]. Each unit was allocated into one of 20 technological clusters according to fuel that is being consumed and technology that is utilized by the generation unit. Exact overview and definition can be found in Egerer *et al.* (2014, p.57).

In the CE region, 607 generation units are present. These are assigned to specific nodes by the method of shortest distance. In the remaining single node countries, all generation units were summed up over the production technology and allocated to that single node. Since no lists of generation units are publicly available[20], all power plants data were overtaken from the study of Egerer *et al.* (2014) whose source was the paid database of World Electric Power Plant database (WEPP) by Platts. The cost of this approach is that the generation dataset reflects the state in the year 2012. Thus an assumption about time-invariant development of generation capacities had to be made for the years 2013 to 2015[21].

Actual generation from individual plants is subject to model optimization

[18]In this sample example, primarily flows in Austrian and Swiss grids would be affected as they transport electricity to Italy from big exporters like Germany or France

[19]Generation units above 10 MW of installed capacity are considered only

[20]Except for Germany which was mentioned earlier

[21]The only exeption is the German nuclear phase-out which was fully reflected in the dataset for the particular period

after taking technical parameters of the plants into account. Insight is given in the section 4.3.4.

Renewables

Unlike in the previous case, non dispatchable renewables, by which we primarily mean solar and wind plants, could not have been accounted for individually due to high degree of decentralization and small installed capacity of individual units. As such, regional aggregation with respect to individual nodes was conducted[22]. As a result, the weights of individual nodes on the total solar and wind generation were obtained. Detailed description of the method can be found in Egerer *et al.* (2014, pp.62,64) and Leuthold (2009).

The renewable generation enters the model as a parameter and for this reason, aggregate data on 2015 hourly generation for the country level were obtained from ENTSOE transparency platform[23]. These were then allocated to individual nodes in accordance with the aforementioned approach.

4.3.4 Time dependent data

In this section, parameters for the conventional power plants will be introduced so that a full picture behind the generation can be constructed. These parameters include fuel cost, generation efficiency and availability of production units.

Fuel cost

In order to obtain model outcome with the specific production from the different generation technologies, fuel and emission prices have to be introduced as these represent the short-term variable costs of producing one megawatt hour of electricity. This applies to conventional power plants whereas solar, wind and hydro power plants are considered at the zero production cost. By both types, operation and maintenance costs as well as unit commitment costs are not considered (Egerer *et al.* 2014).

Input prices for particular inputs are given in the table 4.1 below together with the respective data sources. All prices were updated to 2015 values except the price for coal where only 2014 values were available.

[22] Country-specific nodes were allocated 100% of renewable capacity of the whole country

[23] In case of Italy, no data were available ant hus the site of TERNA, Italian TSO, was consulted

Table 4.1: Fuel prices

Fuel	Price [EUR/MWh$_{th}$], [EUR/t(CO_2)]	Source
Uran	3	Assumption of Egerer et al. (2014)
Lignite	3,48	Own calculation
Hard Coal	6,96	BP: Northwestern Europe coal price 2014
Gas	22,28	EC: Quarterly reports on European gas markets
Oil	28,42	Bloomberg: Brent oil price
Biomass	7,2	Assumption of Egerer et al. (2014)
Hydro	0	
Wind	0	
Sun	0	
Waste	7,2	Assumption of Egerer et al.
Carbon	7,59	EEX: Median CO2 EUA settlement prices

Prices of natural gas and oil do differ across European countries as a result of different location, different transportation costs and various import sources. A country-level factor for each state was thus computed and the prices were multiplied accordingly. Factor calculation was based on publicly available data provided by European Commission[24].

Generation efficiency and availability of generation capacity

These technical features should capture the influence of specific technologies and should thus complete the information necessary for generation calculation.

Power plants work with efficiency that is significantly lower than the fully optimal output of 100%. Despite the fact that these numbers are frequently very low, some technological progress took place during 20^{th} and 21^{st} centuries. Table 4.2 shows the technology-specific efficiencies with respect to time and technlogy.

Availability parameter aims to account for share of non-operation time in generation capacities due to maintenance, outages, etc. Installed capacity of the generation units is multiplied by corresponding percentage which can be found in the table 4.3[25].

[24] Sources: Quarterly reports on European gas markets (https://ec.europa.eu/energy/en/statistics/market-analysis); EU Crude Oil Imports and supply cost (https://ec.europa.eu/energy/en/statistics/eu-crude-oil-imports)

[25] It is important to note, that availability of wind, solar and pump storage power plants is set to one as corresponding data enter the model as external paramters

Table 4.2: Efficiency of conventional generation technologies (in %)

	1950	1960	1970	1980	1990	2000	2010
Nuclear	33	33	33	33	33	33	33
Lignite	29	32	35	38	41	44	47
Coal	29,6	32,8	35,9	39,1	42,3	45,5	48,7
CCGT and CCOT	20	26,7	33,3	40	46,7	53,3	60
Gas Steam and Oil Steam	30,6	33,8	36,9	40,1	43,3	46,5	49,7
OCGT and OCOT	24,7	27,3	29,9	32,5	35,1	37,7	40,3
Source	(Egerer *et al.* 2014, p.70)						

Table 4.3: Availability of conventional generation technologies

Type	Nuclear	Lignite	Coal	CCGT, CCOT	OCGT, OCOT	Gas Steam, Oil Steam	Reservoir, RoR	Hydro
Availability	0,84	0,9	0,87	0,91	0,9	0,89	0,62	0,32
Source:	Egerer *et al.* (2014, p.70) and Schröder *et al.* (2013)							

4.3.5 Load and electricity price

Exact definition of load is given by ENTSOE, which defines it as follows: "Total load includes electricity generation plus imports less exports and power used for electricity storage" (ENTSOE 2015). Due to the necessary balancing in the grid and due to the fact that electricity storage is accounted for separately, these data correspond basically to the amount of electricity demanded. ENTSOE database was the source of hourly data for all included countries for the year 2015.

Primary utilization of the data lied in the necessity to have the counterpart to the generation on nodal basis in CE region and national basis in the rest of countries. Nevertheless, the load values are available on national level only which is not satisfactory for the purposes of the model. Egerer *et al.* (2014) suggests an approach how to estimate the weights of individual nodes. The key parameters are data on GDP and population which serve as proxies for industrial and residential demand respectively[26]. All data are taken on the NUTS 3 level, for which the data are available in all cases (Egerer *et al.* 2014). Exact allocation procedure is described in detail in Egerer *et al.* (2014) and Leuthold *et al.* (2012).

[26]GDP assumes 60% weight whereas population assumes 40%

Secondary utilization of the load data occurs in the optimization problem where the welfare function is maximized. At each node reference demand, reference price and elasticity are estimated in order to identify demand via a linear demand function (Leuthold *et al.* 2012). In here, as Leuthold suggests, the hourly load is assigned to the nodes according to the node's share described in the previous two paragraphs. This, subsequently, yields a reference demand per node. Reference price on country level was obtained from the European commission's Quarterly reports on European energy markets for the year 2015[27]. Table 4.4 shows the prices for relevant countries.

Table 4.4: Electricity reference prices, [EUR/MWh]

Country	AT	CH	CZ	DE	DK	FR	HU	IT	LU	NL	PL	SI	SK	SE
Price	32,33	36,80	32,53	32,08	25,63	38,75	41,45	53,80	32,08	41,73	41,48	41,93	33,50	18,51
Source:	European Commission, DG Energy (2016c)													

The last necessary parameter, demand elasticity, is based on the findings of Green (2007) and is taken as -0.25. Finally, linear demand function is estimated based on these three inputs (see section A).

4.4 Simplification of the full year model

Next-to-last section of this chapter explains the issues that occured during model solution. The original intention was to model full scope of the year 2015, i.e. 8760 hours in the year. Unfortunately, it became clear that this approach had been unfeasible due to hardware limitations resulting from complex structure of the model.

For this reason, alternative approach was applied. With respect to the fact that mostly the extreme values of either load or production are of greatest concern for system stability, representative weeks with the different combinations of extreme values of RES production were used and investigated in detail[28]. As the full year picture is not accessible, it is believed that this approach is the best scond-best option.

[27]The reference price was not subject to nodal allocation. One price for given country is considered

[28]The weeks according to the RES production instead of the load were chosen as this reflects better the nature of the scenarios

Selected weeks

Similarly to the application of Schroeder *et al.* (2013), four weeks[29] with different values of wind and solar production were chosen. In particular, we speek about two base weeks, week 4 and week 14, where the cummulative production from wind and sun was lowest or highest in CE, respectively. In addition to this, also the weeks 27 and 49 are considered which should represent the opposite extremes in production. Thus, week 27 mirrors the situation provided there is a high production from sun and low production from wind and week 49 reflects the opposite.

In the figures 4.2-4.5, the aggregate load-production profiles for CE countries of mentioned weeks are shown on the real data for 2015. Load, residual load[30], sun and wind productions are depicted during the respective hours of the year.

4.5 Border profiles

Due to the fact that there are 30 interconnectors between the states of Central Europe, 29 interconnectors between the German TSOs, another 39 interconnectors between the Central Europe and adjacent states and hundred of lines within the particular countries, commentary on each individual line would not contribute to a lucid and clear interpretation of reuslts. Hence, resulting modeled flows are reported and interpreted on "border profiles"[31]. Full access to unaggregated results is then provided in the appendix A and supplemental materials.

The term "border profile" itself represents the aggregation of all transmission lines that interconnect two neighbouring areas after the model results for individual lines were obtained. There are several kinds of border profiles in this thesis.

Firstly, we include ordinary border profiles between states. The backing idea is that such lines are natural bottlenecks in the contemporary grids (see section 2.2.3) and, therefore, are of greatest interest and importance when interpreting the inlfluence of VRES on transmission networks. Accompanying reason is then

[29]Please note, that we refer here to English-type weeks, i.e. the week starts by Sunday

[30]Residual load is a concept that points to show how much of the remaining load has to be covered by the conventional sources in operation. It is calculated using this simple formula. *Residual load = Load - Sun generation - Wind generation*

[31]This is commonly used approach as can be seen in Egerer *et al.* (2014) for example. Moreover, reasons why such simplification is feasible are given below

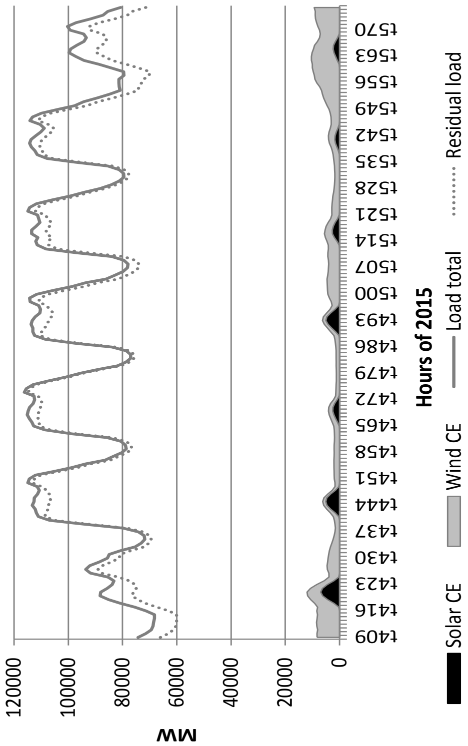


Figure 4.2: Week 4 profile

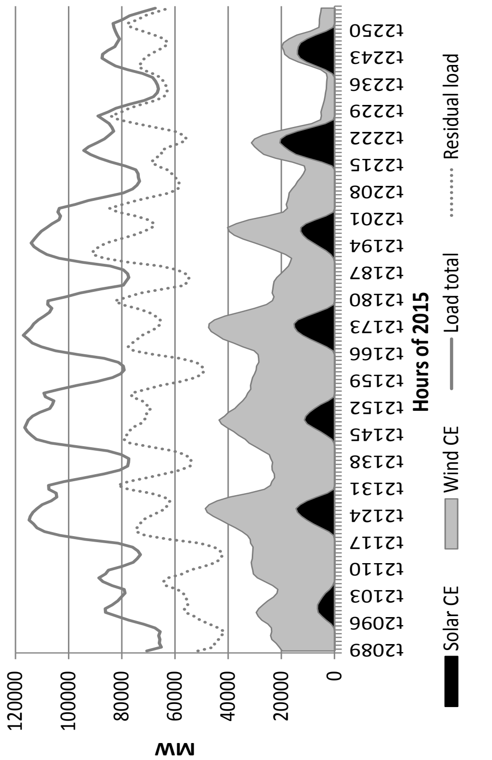


Figure 4.3: Week 14 profile

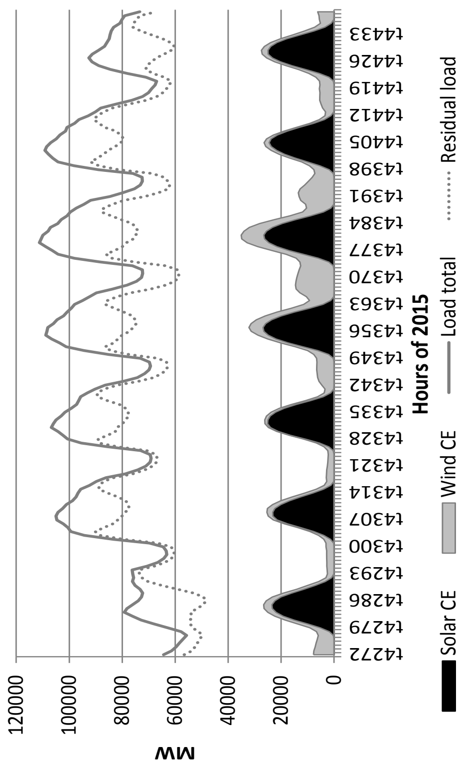


Figure 4.4: Week 27 profile

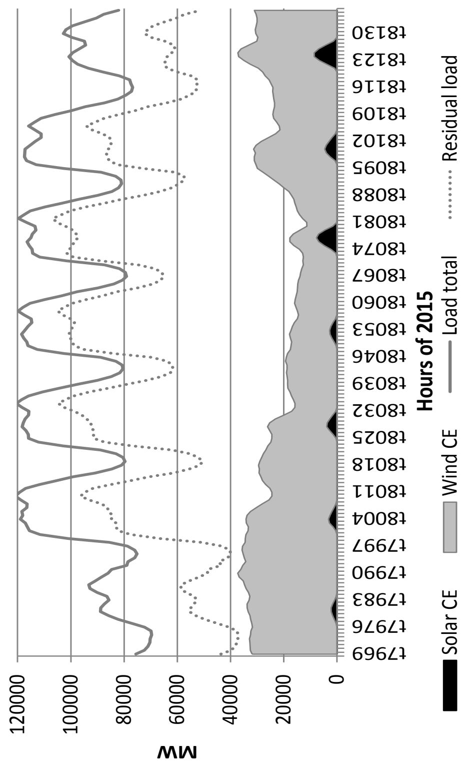


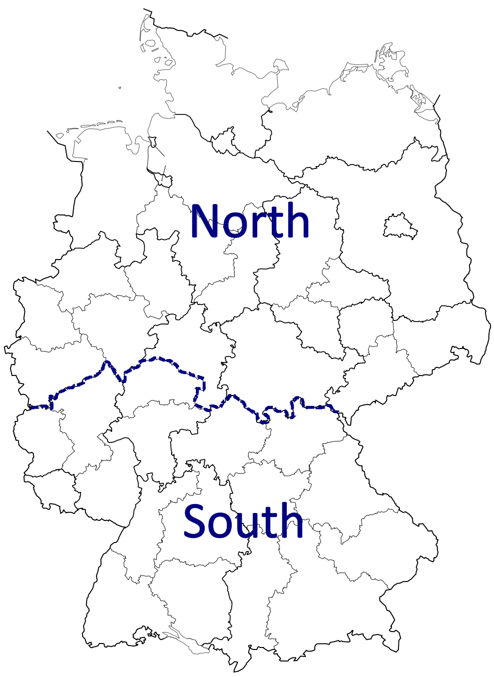
Figure 4.5: Week 49 profile

Source: Own, based on ENTSOE (2016a) data that borders between countries are, as a rule, also borders between individual TSOs and it is desirable to see exchanges and balances between them as these are commonly reported in public databases.

Moving to the border profiles between TSOs, some of such profiles do not necessarily coincide with state borders. This is case of Germany, where four separate TSOs operate in total. The motive for involvement of these profiles slightly differs from the previous one. Profiles between intranational TSOs do not inevitably embody the grid bottlenecks but rather allow for interesting observations of flows between TSO's areas resulting from the distribution of VRES production and consumption centres in Germany (see section 2.2.3).

Last type includes special and, to a large extent, artificial border profile between northern and southern Germany which was employed for the examination of the electricity exchanges with respect to the bottlenecks within Germany as described in the sections 2.2.3 and 2.4.3. This border profile was created similarly to the study of Egerer *et al.* (2015). Graphical representation can be found in the figure 4.6.

Figure 4.6: Division of Germany in northern and southern zones



Source: Wikimedia Commons (n.a.)

Chapter 5

Scenarios and Results

In the chapter 2.4.3, three key issues relating to the transmission networks in Central Europe were identified. To summarize, we refer to:

i) Grid bottlenecks between southern and northern Germany

ii) German Energiewende policy

iii) Market setup (represented by German - Austrian bidding zone)

In the analysis conducted within the scope of this thesis, attention was paid primarily to issues i) and ii). This is implied by the fact that ELMOD model, as employed in this thesis, is not able to reflect market design and assess the impacts of possible design changes[1]. Nevertheless, issue iii) was thoroughly discussed in the section 2.4.3.

5.1 Scenarios

To measure exactly the impact of i) and ii) on the transmission grid, electricity flows on the individual lines within the network were obtained. Afterwards, they were compared in the context of three scenarios.

Base scenario

First scenario, called *base*, took the raw data as specified earlier in chapter 4.3. It basically aims to model the current situation in the power sector and is used as a reference scenario in the analysis.

[1]In a few research works, other market designs than perfect competition were also applied. Neverthless, this requires complete reformulation of the model and approach. For example, Leuthold (2009) uses game theoretic modeling allowing for capturing the factors like cooperation or unwillingness to cooperate among TSOs

Full scenario

Next scenario, called *full*, is the scenario for assesing full range of the impacts of Energiewende policy i) and ii) in CE context. It was derived from the *base* scenario data by taking into account the aims of German energy policy for the year 2025[2]. In practice, this means that parametres reflecting the VRES production were multiplied by coefficients (table 5.1) and nuclear power plants were phased-out. Everything else in Germany as well as remaining countries, including grids, reflect the state of 2015 or other years according to specifications stated in section 4.3. From the nature of construction it thus follows that the results must be read in the context of worst possible outcome which means what would be the impact of flows on the grid if nothing was done in network development.

Derivation of mentioned multiplicative coefficients for VRES production was based on respective Energiewende milestones as specified in the table 2.1.

In the first place, all relevant electricity-related Energiewende goals are defined as a percentage of electricity consumption as compared to the year 2008. According to AGEB (2015), 618.2 TWh of electricity was consumed in Germany in 2008. Energiewende goals require the electricity consumption to be reduced by 10% until 2020 and by 25% until 2050 (BMWi 2015b)[3]. Linear approximation leads us to 12.5% in 2025 which accounts for 541 TWh. This comprises 90.61% of the 2015 consumption.

After having calculated the reference value of consumption, computation of corresponding shares of solar and wind electricity generation can take place. It is based on the scenario "2025 A" from the publication "Netzentwicklungsplan" (Feix *et al.* 2015) where installed capacities are projected. Actual generation was obtained by multiplying these figures by utilization factors[4] of indivudial power plant types that were extracted from AGEB data. This approach yields the renewable/consumption ratio of 45.91%, pretty close to 42.5% which is the

[2]Particular year 2025 was chosen as the reference year due to three reasons. Firstly, it is commonly mentioned in energy projections and some underlying data can be extracted from documentation. Secondly, the growth of renewables is significant enough to allow for monitoring the changes and thirdly, all nuclear power plants are supposed to be out of operation

[3]Actually, the reduction of consumption by 25 % should be due by 2030. Nevertheless, after having look on the development of consumption in recent years, it is clear that this goal seems very ambitious. Consequently, more conservative prediction was taken into account having this aim at the end of the period

[4]Utilization factors are represented by 'full-load hours' - a concept saying how many hours of the years the power plant has to operate at 100 % load to produce the electricity actually generated in given year

result of linear approximation for year 2025 using BMWi scenarios (BMWi 2015b). Table 5.1 summarizes the calculations concisely.

Table 5.1: Parameters of *full* scenario model

TYPE	Installed capacity 2013 (MW) (1)	Development coefficient (2)	Installed capacity 2025 (MW) (3)	Full load hours (4)	Generation 2025 (TWh) (5)	Generation 2015 TWh (6)	Generation coefficient (7)
Solar	36340,00	1,490	54159,61	969,77	52,52	38,50	**1,364**
Wind onshore	33310,00	1,568	52231,66	1900,46	99,26		
Wind offshore	620,00	14,355	8900,00	3118,28	27,75		
Wind	33930,00		61131,66		127,02	86,00	**1,477**
Biomass	8380,00	1,032	8650,32	5000,00	43,25	44,30	
Water	5590,00	1,000	5590,00	3494,62	19,53	19,50	
Other					6,00	5,70	
Source:	Feix *et al.* (2015)	Feix *et al.* (2015)	(1)*(2)	Own, data BMWi (2015b)	(3)*(4)	AGEB (2015)	(5)/(6)

Values given in the column "Generation coefficients" are then that ones, by which original data for wind and solar production were multiplied.

Res scenario

Last scenario, called *res*, is some kind of artificial scenario. It is described by the same charasteristics as the previous one, except the fact that German nuclear power plants are considered to be still in operation even after 2022. The interpretation of this scenario is following: it was included to inspect one particular part of Energiewende policy - the nuclear phase-out or, from the other point of view, isolated impact of renewables on transmission networks without the nuclear phase-out.

5.2 Results

The interpretation of the outcomes of the model is presented in the following manner. First, the results from the *base* model and their fit to the actual data is discussed. We proceed by having look at *res* and *full* scenarios and the development of flows on the lines. Impacts on the border profiles defined in 4.5 is shown by the visualization of imports, exports, balances and the amount of total transmitted electricity. Total transmission is defined as a sum of absolute values of imports and exports whereas the balance is the difference of absolute values of imports and exports[5]. Last part of the analysis referes to a summary statistics for individual international cross-border lines. Above all,

[5]The main difference between balance and transmission is following. Balances measure the electricity after the netting, i.e. electricity, that enters the grid of a respective TSO. Unlike this, transmission is reported to measure the "load" on the particular border profiles

attention is paid to average load, flow magnitudes, volatily and occurences of extraordinaroy load.

For the sake of brevity, detailed commentary is made for the weeks 14 and 4 where peak and bottom of cummulative VRES production occured,respectively. For the weeks 27 and 49, only the most important features of the scenarios are stressed as the trends and patterns have very similar meanings.

Eventaully, only the most important figures are given in the core of the thesis, remaining ones can be found in the appendix A (p. III-XV). Unaggredated data are accesible in supplemental materials.

5.2.1 Results for low VRES production - week 4

As figure 4.2 indicates, week 4 corresponds to the lowest level of production from wind and solar power plants. The general effect of low-pitched volatile production is the low international balance (fig. A.1, fig A.3) as well as total transmission of electricity (fig. 5.3 - 5.2).

When the *base* scenario results for exchange balance are compared to the actually observed ones, we can see that the direction of exchanges of electricity matches the actual ones (fig.2.18), except the case of Czech-Slovak and Polish-German border. Despite this fact, week 4 results exhibit quite a poor performance in predictions of amounts. Table 5.1, line 1, summarizes the percentual deviation from real balances. The higher the value in absolute terms, the worse the fit is. The opposite flow directions in the cases of Czech-Slovak and Polish-German borders are represented by the values lower than -100%.

Reversed flow on Czech-Slovak border is structural in this model. In reality, electricity flows from the Czech Republic through Slovakia to Hungary and further to Balkan countries. Nevertheless, Hungary is modeled as one node and Balkan countries are neglected in this model. The result is that electricity thus flows in reversed order - from Hungary to Slovakia and from Slovakia to the Czech republic. This could be solved e.g. by modeling Balkan countries as one additional importing node.

Presumably, the reason for the poor performance in this particular week is linked to the single TSO's area nature of the model. As low share of zero-marginal cost renewable production enters the model, non-zero cost conventional production has to take place to meet the demand. Because of the single

i.e. how electricity flows in both directions and how it actually loads the grid when the electricity is exchanged

TSO in the model, all area is optimzed at once. Therefore, conventional power plants produce at the most possible local level and the necessity for cross-zonal transport of electricity is limited [6].

Moving to the comparison of individual scenarios, table 5.1 gives a summary of the percentual changes in trasmission and absolute value of changes of balances and transmission as compared to the *base* scenario. Graphical representation of the balances and its decomposition into exports and imports for each scenario can be found in figures A.1-A.6 in the Appendix A, figures 5.3 and 5.2 show then the comparisons of transmission among the scenarios with respect to all border profiles.

We can observe an increase in the amount of total transported electricity over on all border profiles, including the inner ones in Germany. The growth ranges from 3,5% on the Czech-Tennet profile to 21,1% on the Czech-Polish profile respectilvely. In absolute terms, greatest rise of 17.28 GWh occurs on the Austrian-German borders from the international profiles. Concerning the German intrastate ones, significant growth between all TSOs can be observed even in the environment of such a low utilization of VRES capacities.

We can see an interesting pattern if the scenarios *res* and *full* are compared between themselves. In the section 2.2.3, expected impacts of nuclear phase-out were discussed. Briefly, negative impacts on the grid were anticipated, especially in the sense of exacerbating the overloading of grids in the north-south direction in Germany and in sense of greater loop flows through Poland and the Czech Republic. As can be seen form the table 5.1 and figures 5.3 and 5.2 this hypothesis cannot be confirmed in the week with low VRES production. The increases in the magnitudes of flows, transmitted electricity (both absolute and relative ones) or the direction of electricity flows are almost unchanged or even decreased. Same impacts can be observed on the unaggregated lines in the figure A.7. Moreover, these patterns can be seen in weeks with much higher VRES electricity inflow as well. Reasoning for such behaviour is thus given there.

Finally, figure A.7 provides an overview of statistics for particular unaggregated international lines[7]. When focusing on the comparison of scenarios *res*

[6]It is important to note that this differs from reality in the sense that there, firstly single TSO areas are balanced and then the cross-zonal balancing takes place. Its commonly found in studies that the more areas and more uncoordination between individual TSO, the less efficient is the setup and the higher are the volumes and costs of congestion management (Kunz & Zerrahn 2016; 2015)

[7]Similar tables for Czech lines, German lines and interconnectors with neighbours of

and *full* to the *base* one, we can see that average utilization of cross border-interconnectors is very low (below 20 %) as a result of low amount of transport as explained in previous paragraphs. Even though some increase of utilization can be observed on all but three lines, the icrease is very modest. The maximal rise of 6,56% was measured over the line Krajnik (PL)-Vierraden (DE).

Concerning the volatility, one of the thesis' hypotheses stated that VRES induce growth of volatility of transmission and, consequently, contribute to the system destabilization. The results support this statement as can be seen form the figure A.7 where volatilities of scenarios *res* and *full* with respect to the *base* were compared. All but three lines evince standard deviation increment and thus more fluctuating flows can be observed. Special attention should be dedicated to the increase of volatility on all lines on Polish-German, Czech-Polish and German-Austrian borders because these are of greatest concern regarding the loop flows discussion (see section 2.4.3 for more). Unlike in the previous case with the average load, the degree of volatility differs between *res* and *full* scenarios. As noted in the section 5.1, the *res* scenario captures the isolated influence of renewables on volatility. The scenario *full* incorporates also nuclear phase-out into this. In both cases, the higher degree of volatility can be observed, but nuclear phase-out further aggravates it. This is in accordance with intuition. By eliminating the nuclear plants, which are base-load operating plants supplying stable amounts of power, volatility naturally increases. The same happens with an inflow highly time-variant solar and wind production.

Lastly, the feature "number of extreme events" denotes as "# extremes" is given in the figure A.7 for the week 4 and in the figure 5.13 as an overview for all weeks. The definition is how many times the flow on the particular line exceeds 75% thermal limit of the line. This limit is taken as a critical value. To remind, each line is subject to a 20 % margin representing the "N-1" criterion of security. Thus, if the flow on the line exceeds 75%, it could be considered as critical.

Within the scope of week 4, only one critical event occured on the line Krajnik-Vierraden. This is due to the fact that the general load is very low.

CE are provided in the supplemental material. Nontheless, we do not sink into detailed commentary here

5.2.2 Results for high VRES production - week 14

Figure 4.3 represents the week 14 which is the timespan where absolute cummulative peak of VRES production occured. We should firstly note that the sense of result from previous subsection is unchanged. Nevertheless, the magnitudes and strengths of effects are notably larger.

Figures A.10 and A.8 show directly the impact of high power and wind feed-in. The flows of electricity over all profiles dramatically rose and constitute multiples of low VRES production. This can be seen both on balances and on total transmission (fig.5.6 and 5.5). Actual total transmission average increased 2.54 times, maximal relative one increased about 3.41 times (CZ-Tennet profile) and maximal absolute one grew by 670.3 GWh (50Hz -Tennet profile).

The comparison of real balances to the modeled ones yields much more satisfactory results than in week 4. Figure A.10 shows it visually, table 5.4 numerically. Direction of the flow does not correspond to reality only on the Czech-Slovak border. Moreover, fit is, on average, much better than in the case of low production. The best fit on the CZ-Tennet border overestimates the actual exchange only by 3,8%. This is quite good news as the peak values of VRES production are of greatest concern when speaking about the grids (again, as referred to in a section 2.2.3).

Scenarios *res* and *full* yield both higher exchanges and larger amount of transmitted electricity as compared to *base* but again the influence of nuclear phase-out, i.e. the difference between *res* and *full* flows, is counterintuitive. Flows in *full* are actually almost the same or lower than in the case of *res* but they were originally expected to be much higher (reasons for this expectations can be found in the section 2.2.3). It is very likely that the answer to this question is hidden in the merit order effect (fig. 2.11). When base-load and cheaply operating nuclear power plants are shut down, electricity supply curve shifts to the left resulting in higher price. This incentivizes more flexible[8] but more expensively operating hard-coal, gas or even oil power plants to produce and supply localy and flexibely the electricity which can smoothen the VRES volatile production. These amounts cannot be naturally enough to smooth all the increase in volatile production but can significantly milder it. The exact effect of the smoothing (and consequently the amount of electricity transport)

[8]The degree of flexibility of each type of power plants can be seen on the time needed for the start of the power plant. A list follows: Hydro plants: ¡1min; Gas turbine: 15 min; CC-gas plant: 2 hours; Hard coal and lignite power plant 4 hours; Nuclear power plant: 120 hours. Source: Schober & Woll (2016)

depends on the magnitude of the merit order shift and on the increase of the production from mentioned conventional power units. Unfortunately, these merit order price-related effects were not exactly measured in this thesis as they exemplify completely independent research question.

Moving to the comparison of scenarios within the scope of the week, we can again observe growth of cross-zonal transport as Energiewende (scenario *full*) and *res* scenario are taken into account. Rouhgly 10% increase occurs on profiles in Germany. The other profiles exhibit various behaviour, ranging from slight decreases to immense growths (fig. 5.4). In particular, sitaution on German-Austrian and German-Polish border is worth mentioning. The profiles face 46.5 % and 19.2% transmission increase, respectively, when *full* scenario is considered. Also the average load on particual lines on these profiles rose (Krajnik-Vierraden even by 18.2%). Intuitively, this is also accompanied by the upturn in critical events growing cummulatively by 16 on all 13 DE-AT lines and by 27 on only two 50Hz-PL lines as compared to the *base* situation.

All in all, analysis of volatility (fig 5.4) can be summarized similarly to the prior case. However, it is important to have in mind that the overall level of volatility is much higher in the week 14. Growth of standard deviation can be observed on the *base-res* basis as well as on the *base-full* basis on all but two lines. Also the *res-full* comparison shows rise in volatility on majority of lines. In all three cases, particularly interconnecotrs between Germany and Austria are under the biggest volatility pressure; highest values achieve 50% increase.

Final comment in this section is dedicated to the assessment of the previous analysis in a broader context. Despite the fact that Northern-Western Europe is not the area of our particular interest, it is very important to mention here that the impact of above mentioned high VRES feed-in together with the scenarios have much more striking impact on this area than on the area of CE (illusration in fig. A.29-A.32). Whilst the increases in flows of electrical current are still in manageable terms in CE, different effect can be measured on the borders of Germany and Netherlands and Germany and France for example. Especially in the former case, the lines are hitting their limits almost continuously. Alltogether 4 interconnectors connect Netherlands and Germany. These lines are subject to very high average load ranging from 57% to 75.5%. Also, 257 critical events occured in the *base* scenario which increased about another 49 when *full* scenario was considered[9]. Slightly better situation can be seen in

[9]These are results obtained from the model as well but are not subject to publishing in the thesis. Nevertheless, they can be found in the supplemental materials

the latter case of German-French borders. After all, these amounts represent very critical values for the system manageability and stability.

5.2.3 Results for high VRES production - weeks 27 and 49

Only short remark on the meaning and interpretation of the weeks 27 and 49 will be made here. These two weaks are actually a special case for high VRES grid feed-in. Week 27 (fig. 4.4) represents high share of production from wind and low share of production from sun. Week 49 (fig 4.5) mirrors exactly the opposite. Patterns of the results are very similar to the week 14. In spite of this, several things should be stressed.

Regarding the week 27, we can see quite a low volume of international transmission (table 5.7, fig. 5.9 and 5.8) and balances (fig. A.15-A.20). The only exception are the border profiles between Germany and Austria and between the Czech Republic where the balances as well as the transmission is extremely high as compared to the week 4. Moreover, *res* and *full* scenarios induce further growth. The backing idea for the high exchange on these two profiles is based on the regional distribution of solar power plants that are located mainly in southern Germany (Bavaria) and southern Moravia from which the electricity into Austria is imported. Volatility analysis provides another interesting observation. Due to the fact, that solar production itself is very volatile (reverse-parabolic shape of production during day, nothing at night), we can see very high volatility growth in the week-to-week comparison as well as in the base-res-full comparison.

Week 49 (fig. 4.5) is very similar to the week 14. It is just worth mentioning that the transmission and balances are even greater than in the week's 14 case on all profiles but the German-Austrian one where it is lower (table 5.10, fig.5.12-5.11 and A.22-A.27). This is the outcome of the wind production in the north and no solar production in the south. The electricity flows from north to the south of Germany and through neighbouring states as described in the figure 2.18. The effect of loop flows is thus strengtened. The same situation occures on the interconnectores on western and northern German borders as described in the previous section 5.2.2. The only difference is that the impacts are even more serious.

5.2.4 Figures and tables

Flow direction:		CZ - PL	CZ - SK	CZ - AT	CZ - 50Hz	CZ - TENNET	PL - DE	DE - AT	PL - SK	50Hz - TENNET	TENNET - AMPRION	TENNET - TransnetBW	TransnetBW - AMPRION	DE-N - DE-S
Model vs. real balances deviation (% of base flow ; - underest., + overest.)		-82,4%	-111,6%	-81,8%	-30,5%	-86,2%	-100,4%	-78,1%	-89,4%					
Balance increse, GWh	*res*	-5,37	-1,33	2,31	7,81	-1,63	21,63	13,56	-2,80	19,56	14,44	6,42	3,48	0,50
	full	-6,97	-3,08	-1,06	7,77	-3,04	25,38	10,77	-3,88	14,62	4,86	3,75	0,30	-7,41
Transmission increase from the *base*, GWh	*res*	9,31	3,48	5,42	13,61	1,96	8,29	16,44	3,44	45,95	63,48	12,75	15,38	53,24
	full	9,34	4,03	5,52	12,06	1,66	10,12	17,28	3,15	40,47	60,55	11,44	15,21	49,41
Transmission increase from the *base*, %	*res*	21,0%	6,3%	5,8%	39,1%	4,1%	20,1%	16,5%	18,8%	10,6%	14,6%	12,3%	15,4%	14,3%
	full	21,1%	7,3%	5,9%	34,7%	3,5%	24,6%	17,3%	17,3%	9,3%	14,0%	11,0%	15,2%	13,3%

Figure 5.1: Week 4: changes

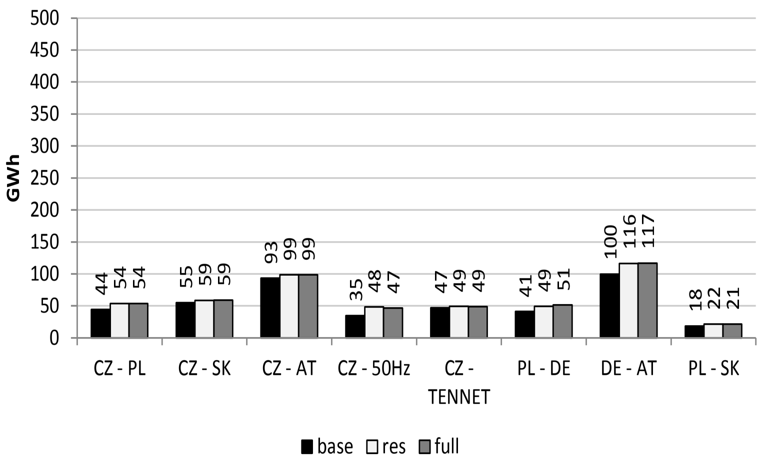


Figure 5.3: Transmission CE, W4

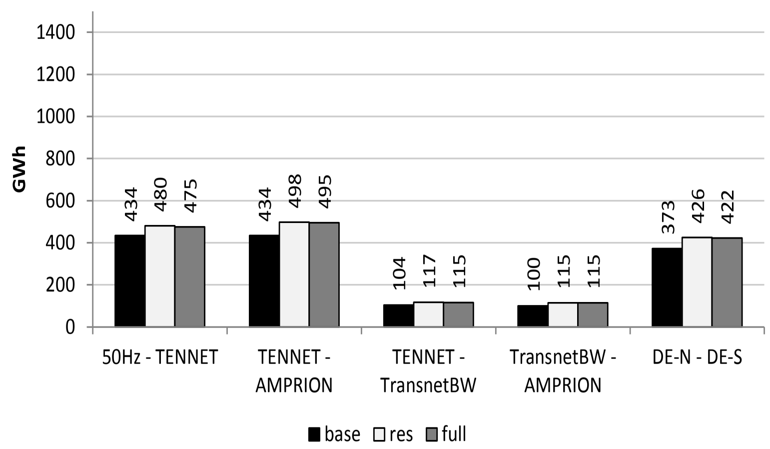
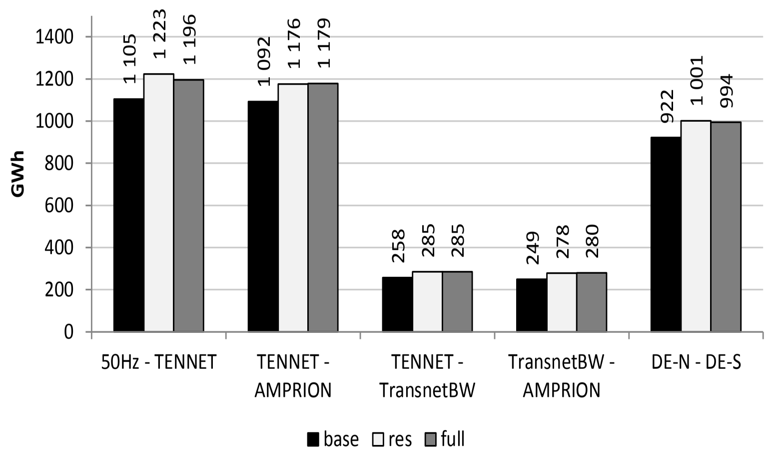


Figure 5.2: Transmission DE, W4

Flow direction:		CZ - PL	CZ - SK	CZ - AT	CZ - 50Hz	CZ - TENNET	PL - DE	DE - AT	PL - SK	50Hz - TENNET	TENNET - AMPRION	TENNET - TransnetBW	TransnetBW - AMPRION	DE-N - DE-S
Model vs. real balances deviation (% of base flow ; - underest., + overest.)		-24,5%	-119,0%	42,6%	70,3%	3,8%	-77,0%	20,2%	-34,1%					
Balance increse, GWh	*res*	-6,51	-12,58	9,12	19,52	-7,04	66,88	72,47	-1,10	4,13	85,20	27,83	25,58	-11,63
	full	-7,36	-18,37	-0,27	18,63	-10,95	65,90	62,33	-0,54	-13,42	79,87	26,35	28,08	-14,57
Transmission increase from the *base*, GWh	*res*	-2,91	-0,10	9,97	18,33	-4,44	39,84	74,91	0,67	118,59	84,52	27,37	29,25	79,38
	full	-4,40	4,42	1,17	17,41	-6,28	40,68	62,87	0,89	90,79	87,03	26,57	31,03	72,33
Transmission increase from the *base*, %	*res*	-2,7%	-0,1%	4,7%	15,4%	-4,6%	45,5%	22,8%	1,3%	10,7%	7,7%	10,6%	11,7%	8,6%
	full	-4,1%	3,7%	0,6%	14,6%	-6,5%	46,5%	19,2%	1,7%	8,2%	8,0%	10,3%	12,5%	7,8%

Figure 5.4: Week 14: changes

Figure 5.5: Transmission DE, W14



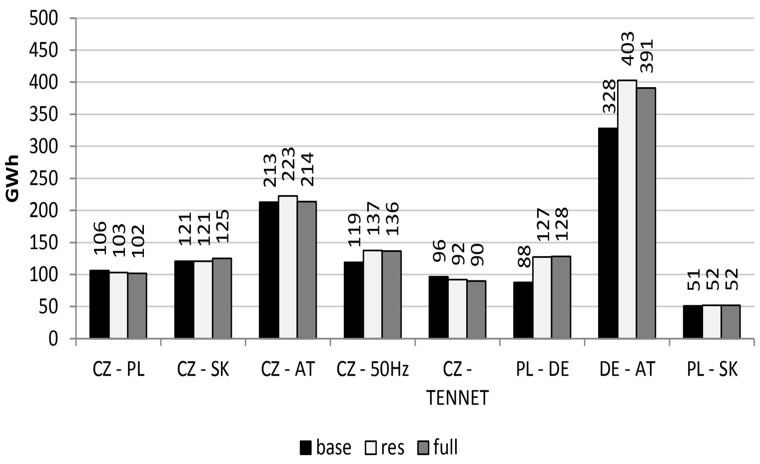


Figure 5.6: Transmission CE, W14

Flow direction:		CZ - PL	CZ - SK	CZ - AT	CZ - 50Hz	CZ - TENNET	PL - DE	DE - AT	PL - SK	50Hz - TENNET	TENNET - AMPRION	TENNET - TransnetBW	TransnetBW - AMPRION	DE-N - DE-S
Model vs. real balances deviation (% of base flow ; - underest., + overest.)		-77,1%	-105,2%	-33,8%	-63,7%	-55,9%	-88,3%	38,6%	-81,3%					
Balance increse, GWh	*res*	-11,49	-1,26	11,81	19,15	-7,39	45,88	72,01	-6,58	49,58	55,32	24,64	23,94	5,63
	full	-6,98	-0,11	22,83	27,31	-4,36	57,70	84,69	-4,12	71,97	115,34	35,88	30,67	38,42
Transmission increase from the *base*, GWh	*res*	6,15	-2,74	10,17	13,75	-1,97	29,85	64,65	2,28	81,44	60,21	20,12	29,15	53,67
	full	12,41	0,98	18,08	21,90	0,66	44,87	71,81	4,28	94,06	108,06	29,55	34,77	94,60
Transmission increase from the *base*, %	*res*	14,4%	-4,8%	7,0%	29,7%	-4,8%	66,9%	21,4%	11,4%	12,9%	7,9%	11,0%	15,0%	9,5%
	full	29,0%	1,7%	12,4%	47,3%	1,6%	100,5%	23,7%	21,5%	14,9%	14,2%	16,1%	17,9%	16,7%

Figure 5.7: Week 27: changes

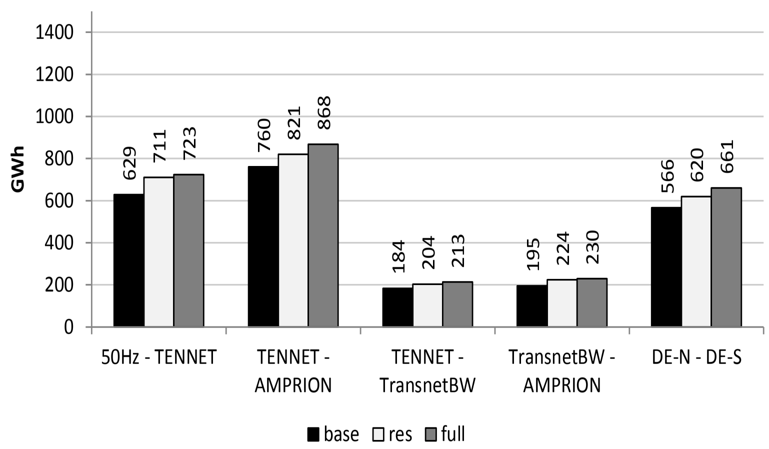


Figure 5.8: Transmission DE, W27

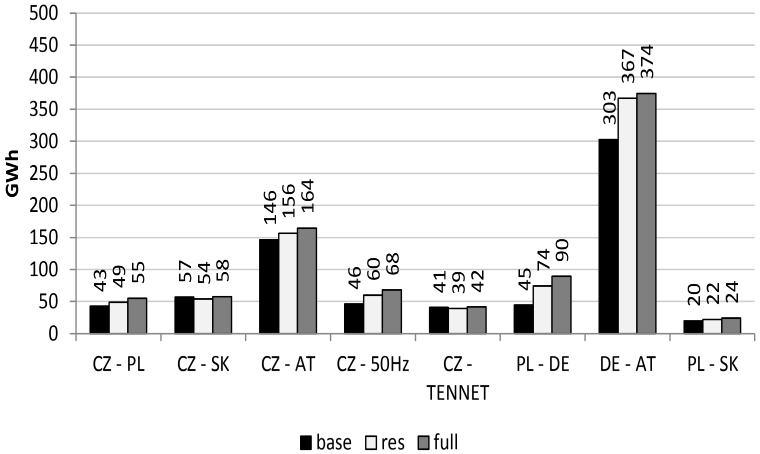


Figure 5.9: Transmission CE, W27

Flow direction:		CZ - PL	CZ - SK	CZ - AT	CZ - 50Hz	CZ - TENNET	PL - DE	DE - AT	PL - SK	50Hz - TENNET	TENNET - AMPRION	TENNET - TransnetBW	TransnetBW - AMPRION	DE-N - DE-S
Model vs. real balances deviation (% of base flow ; - underest., + overest.)		-40,6%	-95,8%	-8,0%	-10,6%	-31,5%	-69,9%	-31,4%	-42,6%					
Balance increse, GWh	*res*	10,59	3,35	24,40	21,13	4,01	37,64	55,29	6,38	55,60	83,93	32,71	24,92	25,46
	full	2,29	-0,83	19,10	15,14	0,58	48,63	49,69	1,73	25,37	69,43	28,35	23,67	12,16
Transmission increase from the *base*, GWh	*res*	-0,61	2,89	20,48	19,32	1,73	10,31	52,55	0,46	149,74	112,93	32,44	30,44	108,25
	full	-4,34	-0,39	17,34	13,33	-0,46	21,66	50,63	-1,46	109,31	94,39	28,09	29,03	90,30
Transmission increase from the *base*, %	*res*	-0,4%	1,9%	9,9%	11,5%	1,7%	9,3%	19,8%	0,6%	12,7%	10,1%	12,4%	12,6%	10,8%
	full	-3,1%	-0,3%	8,4%	8,0%	-0,4%	19,4%	19,1%	-1,9%	9,3%	8,4%	10,7%	12,0%	9,0%

Figure 5.10: Week 49: changes

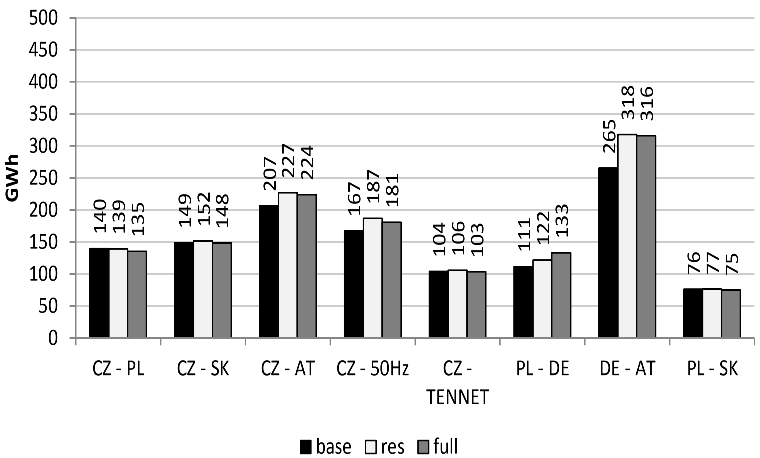


Figure 5.12: Transmission CE, W49

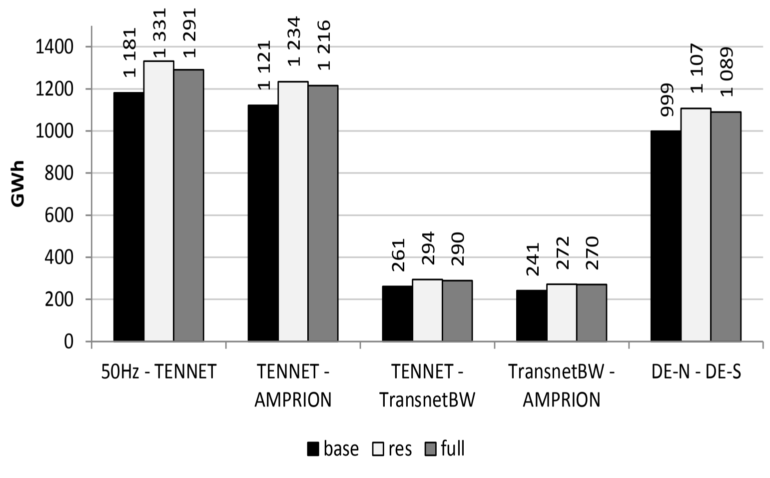


Figure 5.11: Transmission DE, W49

		Substations	Bujakow-Lískovec	Lískovec-Kopanina	Wielopole-Nošovice	Albrechtice-Dobrzeń	Varín-Nošovice	Slavětice-Dürnrohr	Sokolnice-Stupava	Sokolnice-Křižovany	Sokolnice-Bisamberg	Považská Bystrica-Lískovec	Senica-sokolnice	Hradec II-Etzenricht	Hradec I-Röhrsdorf	Přeštice-Etzenricht	Lemešany-Krosno Iskrzynia
		Interconnector	PL=>CZ	CZ=>PL	PL=>CZ	CZ=>PL	SK=>CZ	CZ=>AT	CZ=>SK	CZ=>SK	CZ=>AT	SK=>CZ	SK=>CZ	CZ=>Tennet	CZ=>50Hert	CZ=>Tennet	PL=>SK
		thermal limit	490	490	1700	1700	1700	3400	1700	1700	980	490	490	1700	3400	1700	3400
		line	line138	line139	line155	line156	line523	line536	line537	line541	line571	line585	line586	line1179	line1180	line1181	line395
w4	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w4	res	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w4	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w14	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w14	res	# extrems	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w14	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w27	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w27	res	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w27	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w49	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w49	res	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w49	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

		Substations	Aux-Oberbayern-Bürs	Vöhringen West-Bürs	Bürs-Obermorrweiler	Obermorrweiler-Bürs	Pirach-Sankt Peter	Altheim-Sankt Peter	Simbach-Sankt Peter	Pleinting-Sankt Peter	Leupolz-Westtirol	Leupolz-Westtirol	Bürs-Grünkraut	Pleinting-Sankt Peter	Sankt Peter-Pirach	Mikulowa-Neuerbau	Krajnik-Vierraden
		Interconnector	DE=>AT	DE=>AT	AT=>DE	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	AT=>DE	DE=>AT	AT=>DE	PL=>DE	PL=>DE
		thermal limit	980	490	1700	1700	490	490	490	490	490	1700	490	490	490	3400	980
		line	line1166	line1167	line1168	line1169	line1170	line1171	line1172	line1173	line1174	line1175	line1176	line1177	line1178	line1206	line1207
w4	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**
w4	res	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w4	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
w14	base	# extrems	-	-	-	-	-	-	**1**	-	-	-	-	-	-	-	**13**
w14	res	# extrems	**3**	-	-	-	-	-	**3**	**6**	-	-	-	**6**	-	**1**	**46**
w14	full	# extrems	**8**	-	-	-	-	-	**3**	**3**	-	-	-	**3**	-	-	**40**
w27	base	# extrems	**5**	-	-	-	-	-	**10**	**6**	-	-	-	**6**	-	-	-
w27	res	# extrems	**4**	-	-	-	-	-	**28**	**14**	-	-	-	**16**	-	-	**3**
w27	full	# extrems	**3**	-	-	-	-	-	**44**	**17**	-	-	-	**18**	-	-	**5**
w49	base	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**17**
w49	res	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**38**
w49	full	# extrems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**49**

Figure 5.13: Extreme load overview

5.2.5 Limitations of the model

Despite the fact that the model was created in a belief to capture the reality most precisely, some simplifying assumptions had. The relaxation of these assumptions and thus removal of consequent limitations can be considered a great opprortunity for author's or other researchers' further work.

Firsty, as a result of immense computational difficulty, simplification of alternating current (AC) load flow to a direct current (DC) load flow was used. This allowed for linearization at the cost of some restrictive assumptions causing lower level of flow accuracy.

Second issue concerns the transmission networks which are static in the model and reflect the state of the year 2012 also in the scenario *full* and *res* whose reference year is 2025. From this perspective, the results must be read in the context of "worst possible scenario" outcome which means what would the impact of flows on the grid be if nothing was done in network development. Incorporation of lines that are expected to be built would result in more precise conclusions in the sense of real policy applications.

Next limitation regards the *ceteris paribus* nature of the model. When assessing the impact of scenario *res* and *base*, only the parametres in German power system were adjusted. Even though the measurement of all other factors was not ambition of this thesis, incorporation of Energy Conceptions of other involved countries would deliver even more real-world results.

Certain distortion of reality also occurs as a result of not incorporating all ENTSOE member countries into the analysis. In particular, absence of a node for Balkan countries cause reversal of direction of electricity flows on Czech-Slovak borders. An addition of such node would fix the issue.

Last limitation covers the assumptions of perfect competition and welfare maximization from the perspective of the external social planner. In the former case, oligopolistic design of the market would probably reflect the reality better. A wide range of advanced tools addressing this issue could be considered. For instance, Leuthold (2009) proposes the method of "Game Theoretic Economic Engineering Modeling". Another approach includes the agent-based modeling. Nevertheless, all these options require significant, deep and quite complicated restructuring of the current model. Regarding the social planner, concpets from the field of political economy such as rent seeking, lobbying or cost of political institutions could be employed in the model.

Chapter 6

Conclusion

The thesis thoroughly examined power and transmission systems in Central Europe. History of German energy transition and energy laws was described so that the causes of the power system structural changes in CE could be observed. Next, consequences of the policies on transmission systems both in national and international contexts were described. Three key issues were identified: i) the capacity of the grid in Germany does not correspond to the needs emerging from Energiewende which creates grid bottlenecks between norhtern and southern Germany, ii) this induces the electricity to flow through the energy systems of neighbouring states and iii) current market design in the form of German-Austrian bidding zone further exacerbates the problems.

Chapter 3 gave an overview of feasible modeling approaches and relevant literature. Due to the neccesity to capture specific electricity related restrictions to see the influence on the infrastructure, ELMOD model was chosen to model the effects. ELMOD can be classified as a large scale non-linear bottom-up optimization model maximizing general social welfare fucntion under production and transmission constraints and under the assumptions of single TSO and of perfect competition among market players.

Chapter 4 introduced the model formulation and data description. Simplification to four representative weeks was explained and role of border profiles in the interpretation of results was sketched.

In the Chapter 5, results were presented. Several important findings were revealed. First of all, the higher is the feed-in of solar and wind power plants, the higher is the exchange balance and total trasport of electricity between TSO areas. This holds for international cross-border profiles as well as for inner-Germany's ones. The rise in flows leads also to increase in number of critical events which directly endanger grid stability. Furthermore, model results fit the real values much better under the peak VRES production. This is important feature of the model as the high amounts of volatile inflows are of substantial importance when examining transmission grids. Additional analysis found that while the situation remains manageable in Central Europe, the Nort-Western Europe should be concerned about this issue much more.

Two scenario developments, *full* and *res*, were examined. The first one attempted to measure the *ceteris paribus* effect of German Energiewende on the transmission networks, especially in the context of Central Europe. The latter one dropped out nuclear phase-out and thus assessed isolated *ceteris paribus* impact of increased solar and wind power production.

In the case of *res*, all expectation were met. Amount of cross- border transmission grew both on intranational lines as well as on the cross-zonal ones; so did the average load on majority of particular lines. Moreover, significant rise in volatility of flows was observed.

In the case of *full* scenario, initial hypothesis was partially rejected. This stated that nuclear phase-out further exacerbates the congestion (especially between norhtern-southern Germany) and causes volatility growth. Surprisingly, it was revealed that nuclear phase-out does not significantly contribute to the amount of transmission as well as to the average load on lines; instead, these remain almost unchanged or slightly decrease. Reasoning for this behaviour lies presumably in the merit order effect. On the other hand, results suggest that volatility grows as nuclear plants are shut down. This is in accordance with intuition as the nuclear power plants supply stable base-load output.

Finally, focus on separate peaks in solar and wind production showed that the combination of high solar and low wind feed-in induces greatly the volatility and cross-border flows on the Czech-Austrian and German-Austrian borders. On the contrary, low solar and high wind production leads to the highest observed flows within Germany as well as on transnational lines, except the ones on German-Austrian borders. Thus, electricity loop flows through other Central European countries take up on intensity.

Despite the results, there is still a lot of space for further research. The ceteris paribus changes could be replaced by incorporation of parametres and variables according to the Energy conceptions of all states, perfect competition and one TSO assumption could be replaced by oligopolistic strucutres backed by game theoretic approach and external social planner could be replaced by political institutions.

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Appendix A

Appendix

Derivation of demand function coefficients

Linear inverse demand function takes the form of:

$$\pi_{nt} = A_{nt} + D_{nt} q_{nt} \tag{A.1}$$

By rearranging:

$$q_{nt} = -\frac{A_{nt}}{D_{nt}} + \frac{1}{D_{nt}} \pi_{nt} \tag{A.2}$$

Standard price elasticity takes the form of:

$$\epsilon = \frac{\partial q_{nt}}{\partial \pi_{nt}} \frac{\pi_{nt}}{q_{nt}} = \frac{\pi_{nt}}{D_{nt} q_{nt}} \tag{A.3}$$

Elasticity is treated as an external parameter and, as such, is known at the reference point $(\pi_{nt}^{ref}, q_{nt}^{ref})$. Exact value of the elasticity accounts for -0.25. Backing reasons can be found at the end of section 4.3.5. Hence, price A_{nt} and slope D_{nt} can be calculated at each node and for each time period:

$$D_{nt} = \underbrace{\frac{1}{\epsilon} \frac{\pi_{nt}^{ref}}{q_{nt}^{ref}}}_{<0} \tag{A.4}$$

$$A_{nt} = \pi_{nt}^{ref} - D_{nt} q_{nt}^{ref} = \underbrace{\pi_{nt}^{ref} \left(1 - \frac{1}{\epsilon}\right)}_{>0} \tag{A.5}$$

Derivation of supply function coefficient

The supply function coefficient M_{nc} is based on the common calculation of marginal cost of electricity. The formula applied in this thesis is based on the definition given in Schober & Woll (2016). The marginal cost of power plant c at node n has the form of:

$$M_{nc} = \frac{price^{nc}_{fuel} + price^{nc}_{CO_2} \cdot intensity^{nc}_{CO_2}}{efficiency^{nc}} \tag{A.6}$$

Model results - Figures and Tables

All figures and tables in this Appendix are based on outputs from the ELMOD model as conducted in this thesis. The only external data, provided by ENTSOE (2016a), are used for illustration of real balances.

Note: Figures A.3-A.27 are determined by the logic of the direction of lines. For example CZ $\implies$ PL indicates the direction of the line from the Czech Republic to Poland). Exports and imports are defined accordingly. Exports go in hand with line directions (half-plane $y > 0$), imports go against them (half-plane $y < 0$)

Figure A.1: Exchange DE, W4, *base*

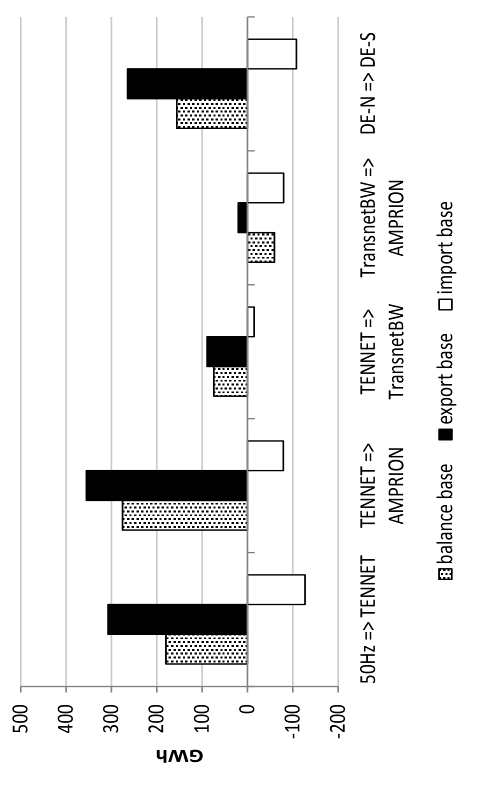
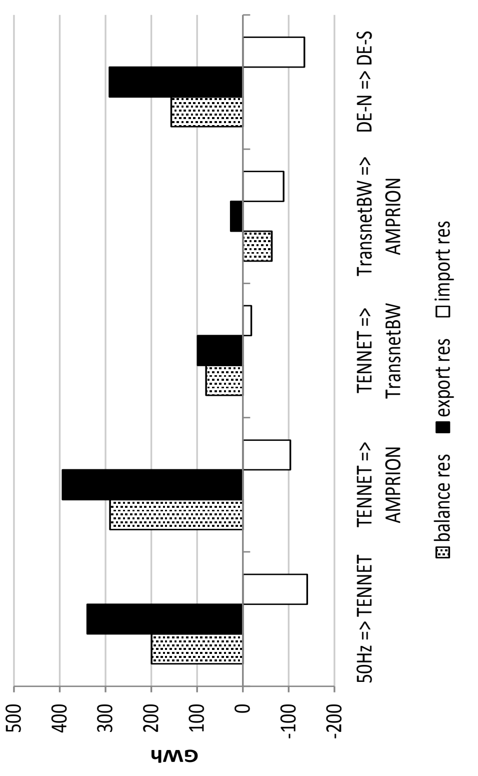


Figure A.2: Exchange DE, W4, *res*



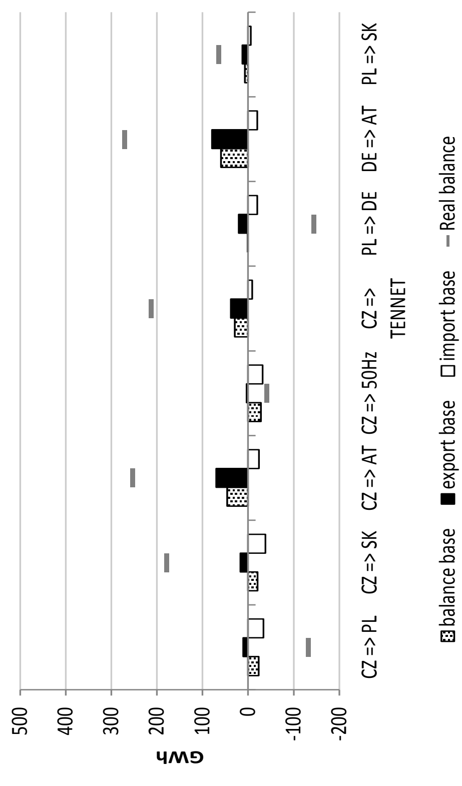


Figure A.3: Exchange CE, W4, *base*

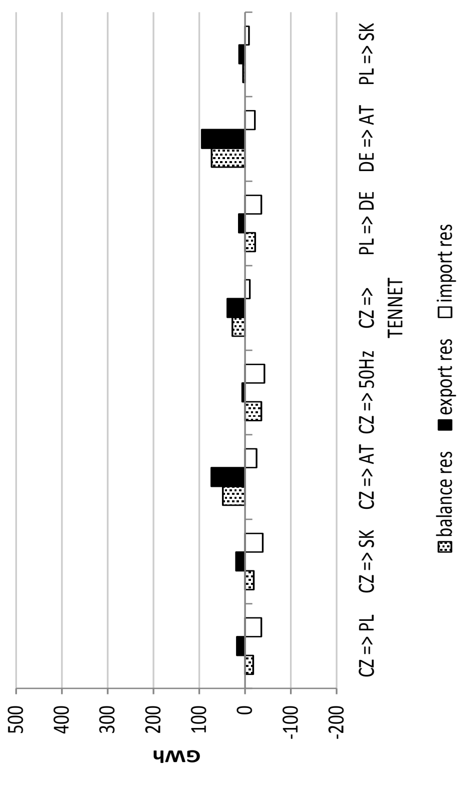
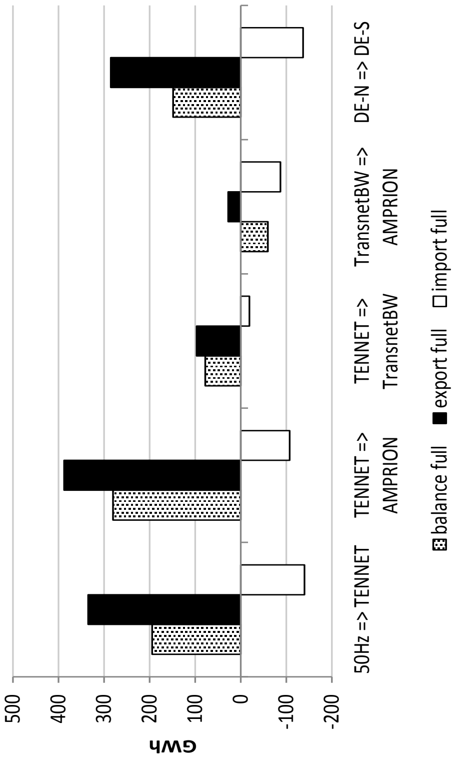


Figure A.4: Exchange CE, W4, *res*

Figure A.5: Exchange DE, W4, *full*



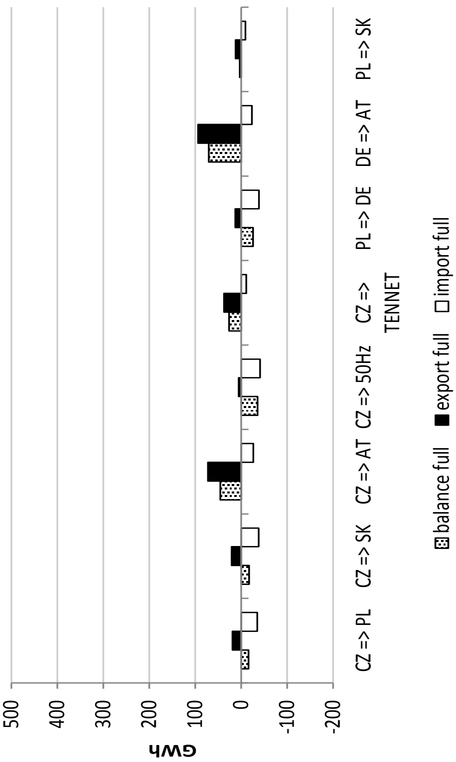


Figure A.6: Exchange CE, W4, *full*

Figure A.7: Analytical summary, W4

		Substations	Bujakow-Lískovec	Lískovec-Kopanina	Wielopole-Nošovice	Albrechtice-Dobrzeń	Varín-Nošovice	Slavětice-Dürnrohr	Sokolnice-Stupava	Sokolnice-Křižovany	Sokolnice-Bisamberg	Považská Bystrica-Lískovec	Senica-sokolnice	Hradec II-Etzenricht	Hradec I-Röhrsdorf	Přeštice-Etzenricht	Lemešany-Krosno Iskrzynia
		Interconnector	PL=>CZ	CZ=>PL	PL=>CZ	CZ=>PL	SK=>CZ	CZ=>AT	CZ=>SK	CZ=>SK	CZ=>AT	SK=>CZ	SK=>CZ	CZ=>Tennet	CZ=>50Hert	CZ=>Tennet	PL=>SK
		thermal limit	490	490	1700	1700	1700	3400	1700	1700	980	490	490	1700	3400	1700	3400
		linka	line138	line139	line155	line156	line523	line536	line537	line541	line571	line585	line586	line1179	line1180	line1181	line395
w4	base	average, MWh	34,308939	42,723241	123,7244	63,146474	56,94326	383,37251	100,41571	107,73867	171,78617	40,06472	22,690798	140,08617	207,15652	140,85206	108,52398
w4	base	average, %	7,00%	8,72%	7,28%	3,71%	3,35%	11,28%	5,91%	6,34%	17,53%	8,18%	4,63%	8,24%	6,09%	8,29%	3,19%
w4	base	min	-236,9433	-122,876	-834,539	-184,7557	-267,6257	-823,3308	-247,9407	-250,4022	-384,6405	-105,9577	-114,9156	-266,5651	-782,2616	-279,7523	-836,1514
w4	base	max	93,697413	287,40164	315,37668	389,68033	330,32651	844,35674	612,94516	546,91734	373,41435	121,65003	52,625083	333,59572	612,61324	334,64555	284,21104
w4	base	st. Dev	44,389493	53,479345	156,49672	75,409587	75,980358	378,57885	111,15865	115,5177	166,46165	53,872111	24,292878	129,18544	218,00542	130,60927	155,59948
w4	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w4	res	average, MWh	40,086826	50,041193	149,88369	79,280857	68,519098	403,69527	102,55833	112,17211	183,70474	41,685804	23,618045	146,16288	288,16135	146,42742	128,97153
w4	res	average, %	8,18%	10,21%	8,82%	4,66%	4,03%	11,87%	6,03%	6,60%	18,75%	8,51%	4,82%	8,60%	8,48%	8,61%	3,79%
w4	res	min	-244,9876	-126,9127	-769,1256	-199,9844	-356,6511	-984,522	-253,2358	-269,4791	-451,0449	-108,4049	-80,81601	-314,2657	-890,3168	-327,4943	-876,0924
w4	res	max	95,932199	242,12419	330,46407	348,37815	310,942	940,65896	325,94199	384,5615	424,57578	120,97386	56,63433	336,46721	764,32658	340,84325	435,94238
w4	res	st. dev	55,046702	65,441276	195,73025	95,928093	91,04728	405,69916	110,13951	121,27905	183,30236	55,806234	25,502904	143,24733	292,46854	144,93	187,99372
w4	res	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w4	full	average, MWh	40,016372	49,969875	150,66914	78,824092	67,547202	404,18251	103,91699	114,77259	183,82133	41,432311	24,165742	145,24673	278,96805	145,58356	127,2846
w4	full	average, %	8,17%	10,20%	8,86%	4,64%	3,97%	11,89%	6,11%	6,75%	18,76%	8,46%	4,93%	8,54%	8,20%	8,56%	3,74%
w4	full	min	-259,4392	-119,6363	-895,1353	-189,8507	-321,5493	-1059,494	-254,3479	-271,5536	-507,9012	-109,4505	-87,74241	-315,5579	-852,2539	-328,8027	-932,7656
w4	full	max	90,346061	310,42941	312,35558	398,8324	325,70951	891,31142	353,20215	417,49847	400,89929	129,89026	57,0703	327,47982	754,41423	326,89577	283,92421
w4	full	st. dev	57,821402	68,695738	205,21296	99,19454	91,973739	413,43691	116,06004	130,36643	187,97411	56,089071	27,410176	144,88077	282,15736	146,8102	197,27238
w4	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

w4	res	Δ avg load, %	1,18%	1,49%	1,54%	0,95%	0,68%	0,60%	0,13%	0,26%	1,22%	0,33%	0,19%	0,36%	2,38%	0,33%	0,60%
w4	full	Δ avg load, %	1,16%	1,48%	1,58%	0,92%	0,62%	0,61%	0,21%	0,41%	1,23%	0,28%	0,30%	0,30%	2,11%	0,28%	0,55%
w4	res	Δst. dev, %	24,01%	22,37%	25,07%	27,21%	19,83%	7,16%	-0,92%	4,99%	10,12%	3,59%	4,98%	10,89%	34,16%	10,96%	20,82%
w4	full	Δst. dev, %	30,26%	28,45%	31,13%	31,54%	21,05%	9,21%	4,41%	12,85%	12,92%	4,12%	12,83%	12,15%	29,43%	12,40%	26,78%

		Substations	Aux-Oberbayern-Bürs	Vöhringen West-Bürs	Bürs-Obermorrweiler	Obermorrweiler-Bürs	Pirach-Sankt Peter	Altheim-Sankt Peter	Simbach-Sankt Peter	Pleinting-Sankt Peter	Leupolz-Westtirol	Leupolz-Westtirol	Bürs-Grünkraut	Pleinting-Sankt Peter	Sankt Peter-Pirach	Mikulowa-Neuerbau	Krajnik-Vierraden
		Interconnector	DE=>AT	DE=>AT	AT=>DE	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	AT=>DE	DE=>AT	AT=>DE	PL=>DE	PL=>DE
		thermal limit	980	490	1700	1700	490	490	490	490	490	1700	490	490	490	3400	980
		linka	line1166	line1167	line1168	line1169	line1170	line1171	line1172	line1173	line1174	line1175	line1176	line1177	line1178	line1206	line1207
w4	base	average, MWh	124,79943	33,381472	48,16274	50,72575	6,8020206	13,581465	21,786149	23,314747	44,607701	165,21036	30,191358	23,562297	7,0456039	159,36572	85,791059
w4	base	average, %	12,73%	6,81%	2,83%	2,98%	1,39%	2,77%	4,45%	4,76%	9,10%	9,72%	6,16%	4,81%	1,44%	4,69%	8,75%
w4	base	min	-129,4841	-61,01992	-181,0644	-128,2067	0,0486074	-72,58981	-22,38617	-147,5264	-42,00802	-155,5821	-82,79676	-149,0928	-57,54935	-1327,697	-738,9164
w4	base	max	374,50791	122,34004	121,72883	190,69985	55,559729	73,450938	169,70264	90,45787	132,67788	491,38957	70,20617	91,418329	-0,050348	280,78555	198,57346
w4	base	st. dev	106,15722	35,519292	61,55371	64,82933	12,451159	19,112481	32,447287	33,104591	37,579408	139,18017	36,130659	33,456088	12,89704	245,50152	129,76398
w4	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
w4	res	average, MWh	143,83234	42,056061	57,154382	60,195889	7,7259735	17,846461	31,156513	22,952605	51,885111	192,16318	32,875488	23,19631	8,0026439	147,73989	146,73826
w4	res	average, %	14,68%	8,58%	3,36%	3,54%	1,58%	3,64%	6,36%	4,68%	10,59%	11,30%	6,71%	4,73%	1,63%	4,35%	14,97%
w4	res	min	-142,1104	-65,18819	-209,5895	-136,6804	0,0717903	-33,66835	-33,92703	-56,99607	-44,63273	-165,303	-94,69462	-57,60124	-72,74508	-1183,175	-650,2947
w4	res	max	449,79783	142,90086	129,77438	220,74294	70,230106	96,105533	227,40423	125,07071	157,93711	584,94039	77,369538	126,39868	-0,074361	268,7088	230,78594
w4	res	st. Dev	130,34197	44,166168	72,341665	76,191373	14,252424	21,500966	43,927162	32,162895	46,2438	171,26986	40,105819	32,504393	14,762809	262,75189	169,43304
w4	res	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w4	full	average, MWh	144,13077	42,565086	58,578704	61,696007	8,4986074	17,738252	30,470167	23,103382	51,71781	191,54356	33,836693	23,348688	8,8029462	155,26659	150,12316
w4	full	average, %	14,71%	8,69%	3,45%	3,63%	1,73%	3,62%	6,22%	4,71%	10,55%	11,27%	6,91%	4,77%	1,80%	4,57%	15,32%
w4	full	min	-243,9958	-76,99092	-202,2573	-136,6251	-130,0005	-34,16477	-34,42927	-56,99607	-61,9322	-229,3738	-91,27326	-57,60124	-72,74508	-1446,887	-733,738
w4	full	max	435,71064	137,95296	129,72184	213,02054	70,230106	100,2505	221,90999	158,9641	152,61118	565,21511	77,500243	160,65195	134,65583	273,36304	178,86357
w4	full	st. dev	132,09955	45,122635	74,351953	78,30864	17,769983	22,022955	42,904841	33,343692	46,496875	172,20715	41,189088	33,697727	18,406333	284,28379	173,07093
w4	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

w4	res	Δ avg load, %	1,94%	1,77%	0,53%	0,56%	0,19%	0,87%	1,91%	-0,07%	1,49%	1,59%	0,55%	-0,07%	0,20%	-0,34%	6,22%
w4	full	Δ avg load, %	1,97%	1,87%	0,61%	0,65%	0,35%	0,85%	1,77%	-0,04%	1,45%	1,55%	0,74%	-0,04%	0,36%	-0,12%	6,56%
w4	res	Δst. dev, %	22,78%	24,34%	17,53%	17,53%	14,47%	12,50%	35,38%	-2,84%	23,06%	23,06%	11,00%	-2,84%	14,47%	7,03%	30,57%
w4	full	Δst. dev, %	24,44%	27,04%	20,79%	20,79%	42,72%	15,23%	32,23%	0,72%	23,73%	23,73%	14,00%	0,72%	42,72%	15,80%	33,37%

Figure A.8: Exchange DE, W14, *base*

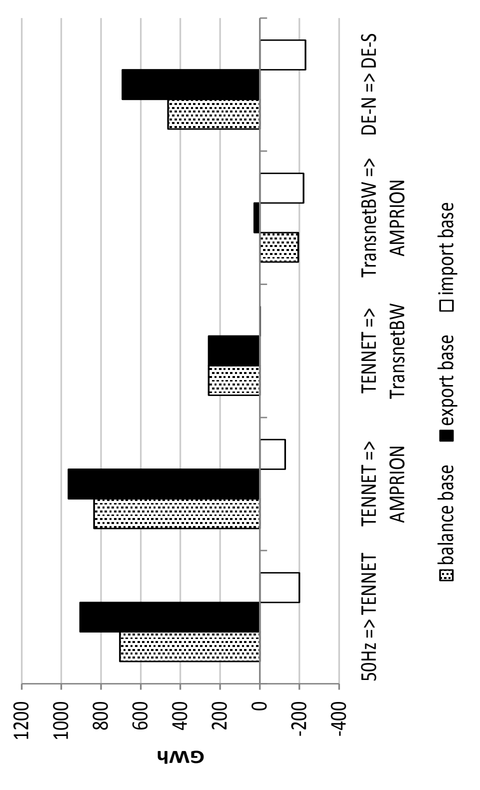
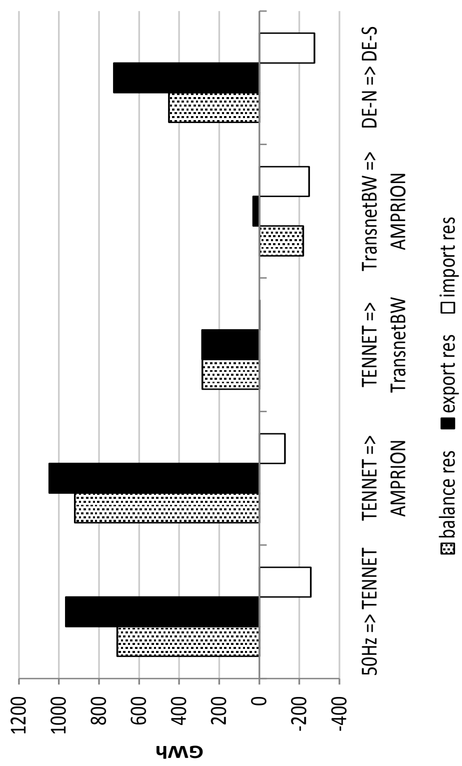


Figure A.9: Exchange DE, W14, *res*



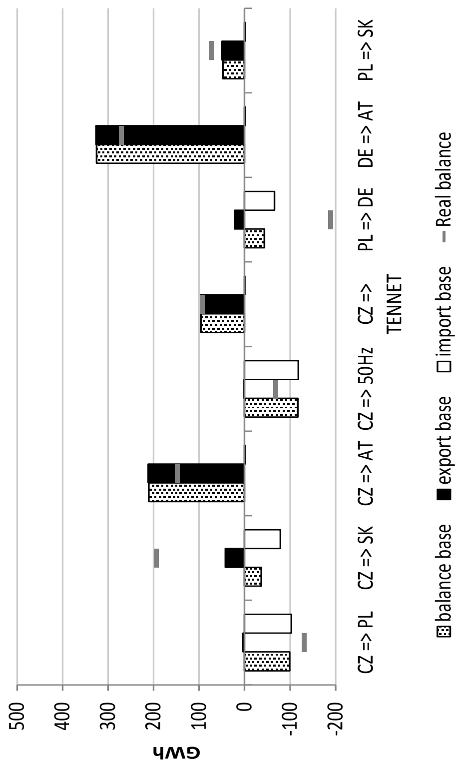


Figure A.10: Exchange CE, W14, *base*

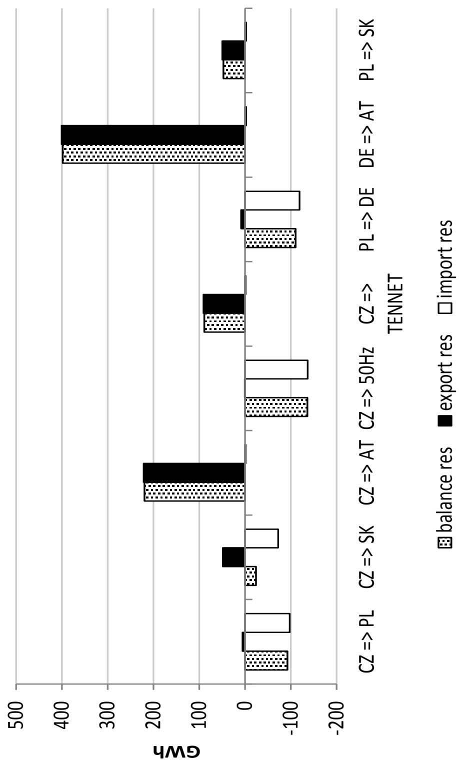
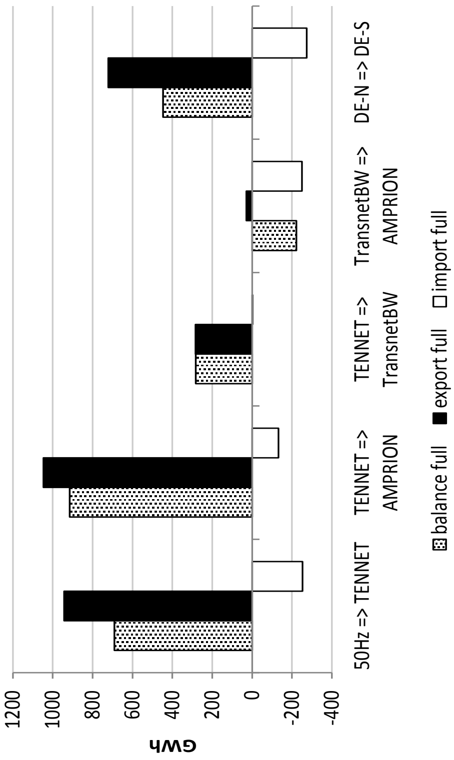


Figure A.11: Exchange CE, W14, *res*

Figure A.12: Exchange DE, W14, *full*



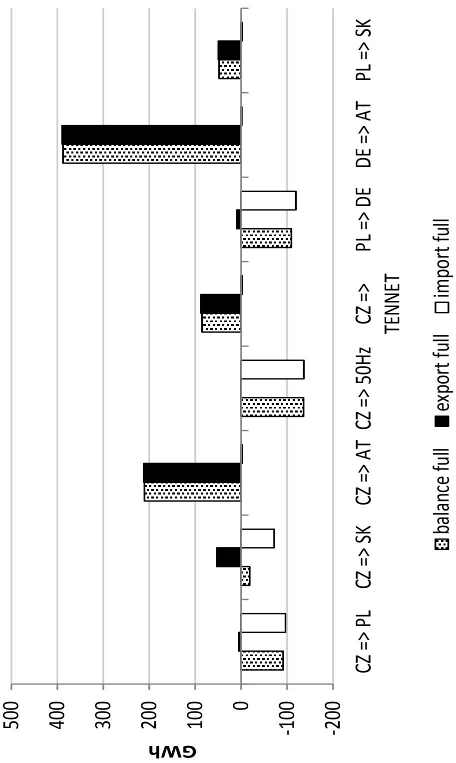


Figure A.13: Exchange CE, W14, *full*

		Substations	Bujakow-Lískovec	Lískovec-Kopanina	Wielopole-Nošovice	Albrechtice-Dobrzeń	Varín-Nošovice	Slavětice-Dürnrohr	Sokolnice-Stupava	Sokolnice-Křižovany	Sokolnice-Bisamberg	Považská Bystrica-Lískovec	Senica-sokolnice	Hradec II-Etzenricht	Hradec I-Röhrsdorf	Přeštice-Etzenricht	Lemešany-Krosno Iskrzynia
		Interconnector	PL=>CZ	CZ=>PL	PL=>CZ	CZ=>PL	SK=>CZ	CZ=>AT	CZ=>SK	CZ=>SK	CZ=>AT	SK=>CZ	SK=>CZ	CZ=>Tennet	CZ=>50Hert	CZ=>Tennet	PL=>SK
		thermal limit	490	490	1700	1700	1700	3400	1700	1700	980	490	490	1700	3400	1700	3400
		linka	line138	line139	line155	line156	line523	line536	line537	line541	line571	line585	line586	line1179	line1180	line1181	line395
w14	base	average, MWh	74,898596	96,056315	299,0661	161,27308	160,59992	858,51269	223,54499	240,46742	407,15208	43,729981	50,751599	289,11341	708,19926	283,96937	305,17656
w14	base	average, %	15,29%	19,60%	17,59%	9,49%	9,45%	25,25%	13,15%	14,15%	41,55%	8,92%	10,36%	17,01%	20,83%	16,70%	8,98%
w14	base	min	-246,7744	-216,6314	-580,0632	-435,0921	-980,9595	-209,665	-395,4764	-443,7328	-91,75476	-151,8692	-147,489	-50,61758	-1891,28	-50,97679	-682,8849
w14	base	max	167,42559	179,5417	716,26362	209,71893	175,72684	1424,3587	956,68593	703,62419	660,33588	146,80385	94,011116	512,86267	240,71359	503,50031	1198,098
w14	base	st. Dev	52,529521	62,687972	190,54968	100,29551	160,79872	354,94232	204,42282	181,40065	165,86704	56,757737	38,092996	130,05629	408,82015	128,09931	227,67038
w14	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w14	res	average, MWh	70,330119	90,789104	291,5409	161,30386	177,34205	901,88292	216,41155	230,82204	423,11656	45,224137	48,692169	277,26927	817,27934	269,36716	309,16932
w14	res	average, %	14,35%	18,53%	17,15%	9,49%	10,43%	26,53%	12,73%	13,58%	43,18%	9,23%	9,94%	16,31%	24,04%	15,85%	9,09%
w14	res	min	-384,0459	-194,1064	-1113,818	-460,137	-960,0506	-492,7551	-338,1903	-366,9837	-264,3159	-166,0679	-133,4804	-280,4265	-1933,594	-323,6573	-1175,47
w14	res	max	147,79304	355,89669	720,33141	205,4938	122,22718	1577,8236	867,7629	637,72329	680,20823	148,19428	77,126115	496,50319	180,00901	486,47947	1182,1013
w14	res	st. dev	56,664016	67,016922	212,69722	107,38133	179,64621	344,75565	221,21568	196,33886	159,19909	57,103298	41,168173	143,56559	426,22139	142,74891	261,49598
w14	res	# extrems	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w14	full	average, MWh	69,795671	88,828359	287,65938	158,81736	178,67246	863,8561	228,78378	239,82567	408,77512	47,568624	50,560483	271,41569	811,81445	264,31399	310,45563
w14	full	average, %	14,24%	18,13%	16,92%	9,34%	10,51%	25,41%	13,46%	14,11%	41,71%	9,71%	10,32%	15,97%	23,88%	15,55%	9,13%
w14	full	min	-278,7325	-224,1628	-809,3139	-474,1336	-1072,809	-634,9911	-345,9334	-381,4816	-312,7535	-242,9447	-156,2317	-285,858	-2046,195	-294,2766	-959,0965
w14	full	max	172,55522	243,87932	767,8941	276,57676	236,91339	1427,6072	954,40867	746,9797	672,33236	160,46009	80,173028	479,30569	217,85966	470,11167	1434,8977
w14	full	st. dev	58,401093	66,025339	211,90101	109,02958	212,48549	340,4457	259,02785	224,83442	157,56672	63,217904	47,129118	149,54886	426,31448	148,15005	289,17571
w14	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w14	res	Δ avg load, %	-0,93%	-1,07%	-0,44%	0,00%	0,98%	1,28%	-0,42%	-0,57%	1,63%	0,30%	-0,42%	-0,70%	3,21%	-0,86%	0,12%
w14	full	Δ avg load, %	-1,04%	-1,48%	-0,67%	-0,14%	1,06%	0,16%	0,31%	-0,04%	0,17%	0,78%	-0,04%	-1,04%	3,05%	-1,16%	0,16%
w14	res	Δst. dev, %	7,87%	6,91%	11,62%	7,06%	11,72%	-2,87%	8,21%	8,23%	-4,02%	0,61%	8,07%	10,39%	4,26%	11,44%	14,86%
w14	full	Δst. dev, %	11,18%	5,32%	11,21%	8,71%	32,14%	-4,08%	26,71%	23,94%	-5,00%	11,38%	23,72%	14,99%	4,28%	15,65%	27,02%

		Substations	Aux-Oberbayern-Bürs	Vöhringen West-Bürs	Bürs-Obermorrweiler	Obermorrweiler-Bürs	Pirach-Sankt Peter	Altheim-Sankt Peter	Simbach-Sankt Peter	Pleinting-Sankt Peter	Leupolz-Westtirol	Leupolz-Westtirol	Bürs-Grünkraut	Pleinting-Sankt Peter	Sankt Peter-Pirach	Mikulowa-Neuerbau	Krajnik-Vierraden
		Interconnector	DE=>AT	DE=>AT	AT=>DE	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	AT=>DE	DE=>AT	AT=>DE	PL=>DE	PL=>DE
		thermal limit	980	490	1700	1700	490	490	490	490	490	1700	490	490	490	3400	980
		linka	line1166	line1167	line1168	line1169	line1170	line1171	line1172	line1173	line1174	line1175	line1176	line1177	line1178	line1206	line1207
w14	base	average, MWh	359,72954	130,57848	190,15494	200,27416	29,021024	63,472714	113,51892	66,511359	130,52806	483,42747	87,699019	67,21756	30,060279	215,59602	305,44185
w14	base	average, %	36,71%	26,65%	11,19%	11,78%	5,92%	12,95%	23,17%	13,57%	26,64%	28,44%	17,90%	13,72%	6,13%	6,34%	31,17%
w14	base	min	-42,53977	-10,82953	-407,3228	-38,3023	-45,16162	-13,93271	-13,88959	-43,45998	-15,65522	-57,98112	-200,8435	-43,92142	-153,288	-1475,039	-784
w14	base	max	704,92365	250,62707	36,367004	428,99874	147,98844	189,99677	370,58968	340,30453	252,88326	936,58565	70,226477	343,9178	46,778881	425,14339	136,60411
w14	base	st. dev	166,37447	57,463458	93,792419	98,783642	38,226858	38,549239	97,428351	61,93827	56,823177	210,45194	50,613162	62,595915	39,595778	310,97222	242,5104
w14	base	# extrems	0	0	0	0	0	0	1	0	0	0	0	0	0	0	13
w14	res	average, MWh	413,34785	156,1203	229,35098	241,55604	38,919917	88,041493	134,92263	112,89117	153,44919	568,31881	106,77238	114,08982	40,313656	265,13749	493,02274
w14	res	average, %	42,18%	31,86%	13,49%	14,21%	7,94%	17,97%	27,54%	23,04%	31,32%	33,43%	21,79%	23,28%	8,23%	7,80%	50,31%
w14	res	min	-27,10104	-8,667368	-545,0456	-19,28821	-165,4691	-11,17954	-11,00579	-22,5907	-10,63881	-39,40222	-281,3625	-22,83056	-209,1965	-2720	-784
w14	res	max	784	315,30466	18,313637	574,05055	201,96404	240,455	392	387,88157	300,06509	1111,3296	44,467886	392	171,39459	360,56892	76,416479
w14	res	st. Dev	175,55907	69,943428	117,70212	123,96571	58,936787	56,489401	106,95226	101,91442	66,305331	245,57032	63,802689	102,99652	61,047339	436,74837	270,3023
w14	res	# extrems	3	0	0	0	0	0	3	6	0	0	0	6	0	1	46
w14	full	average, MWh	404,62578	154,70083	222,6789	234,5289	41,795934	82,532521	128,5182	100,94074	150,63655	557,90182	102,24329	102,01251	43,292664	279,43507	483,76347
w14	full	average, %	41,29%	31,57%	13,10%	13,80%	8,53%	16,84%	26,23%	20,60%	30,74%	32,82%	20,87%	20,82%	8,84%	8,22%	49,36%
w14	full	min	-81,44507	-18,00866	-508,402	-103,5594	-214,0838	-5,991707	-12,60696	-37,4515	-22,62213	-83,78395	-261,4045	-37,84915	-209,1965	-2192,662	-784
w14	full	max	784	301,05213	98,326842	535,45693	201,96404	215,61084	392	387,88157	284,81194	1054,8376	77,130067	392	221,75018	318,91275	76,416479
w14	full	st. dev	188,02211	71,196454	117,15328	123,38767	56,962103	52,264784	106,3142	91,424696	67,508491	250,02637	63,432241	92,395421	59,00194	403,10052	265,67944
w14	full	# extrems	8	0	0	0	0	0	3	3	0	0	0	3	0	0	40
w14	res	Δ avg load, %	5,47%	5,21%	2,31%	2,43%	2,02%	5,01%	4,37%	9,47%	4,68%	4,99%	3,89%	9,57%	2,09%	1,46%	19,14%
w14	full	Δ avg load, %	4,58%	4,92%	1,91%	2,01%	2,61%	3,89%	3,06%	7,03%	4,10%	4,38%	2,97%	7,10%	2,70%	1,88%	18,20%
w14	res	Δst. dev, %	5,52%	21,72%	25,49%	25,49%	54,18%	46,54%	9,78%	64,54%	16,69%	16,69%	26,06%	64,54%	54,18%	40,45%	11,46%
w14	full	Δst. dev, %	13,01%	23,90%	24,91%	24,91%	49,01%	35,58%	9,12%	47,61%	18,80%	18,80%	25,33%	47,61%	49,01%	29,63%	9,55%

Figure A.14: Analytical summary, W14

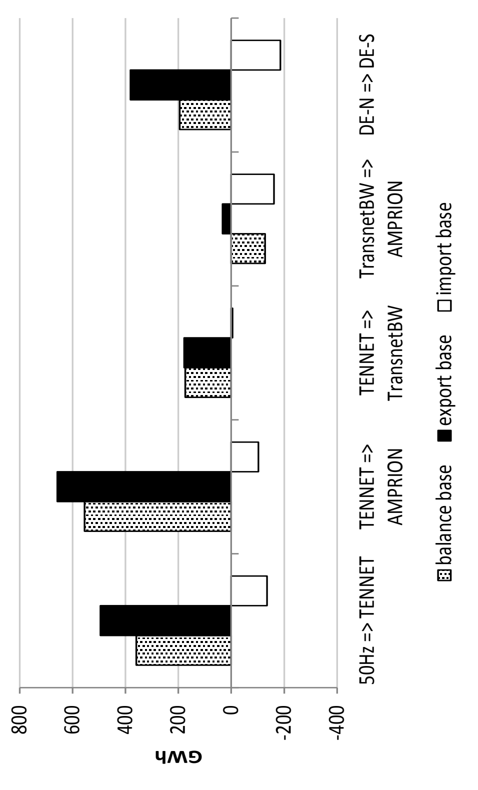


Figure A.15: Exchange DE, W27, *base*

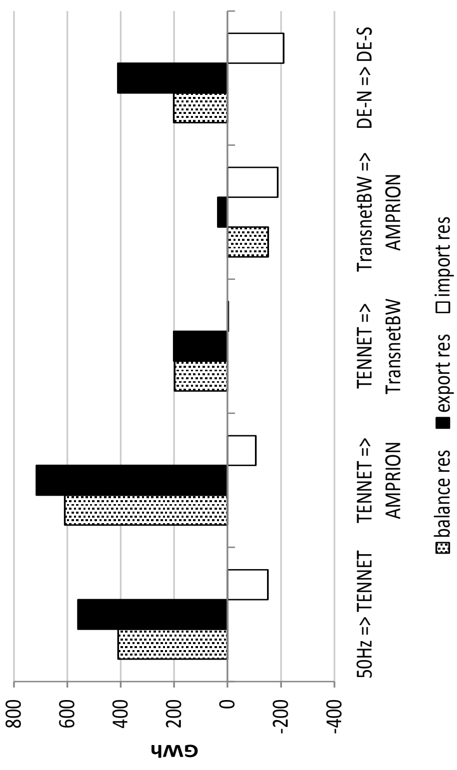


Figure A.16: Exchange DE, W27, *res*

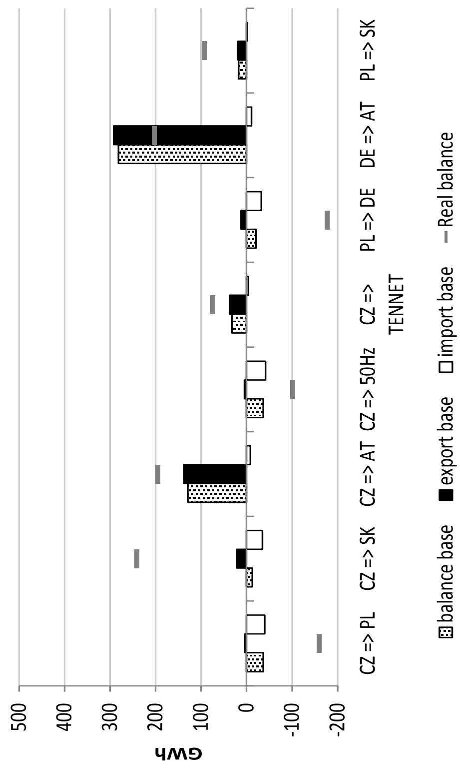


Figure A.17: Exchange CE, W27, *base*

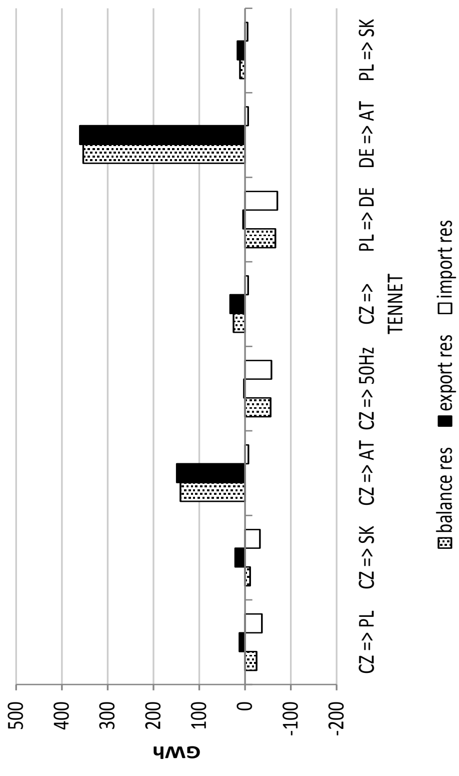
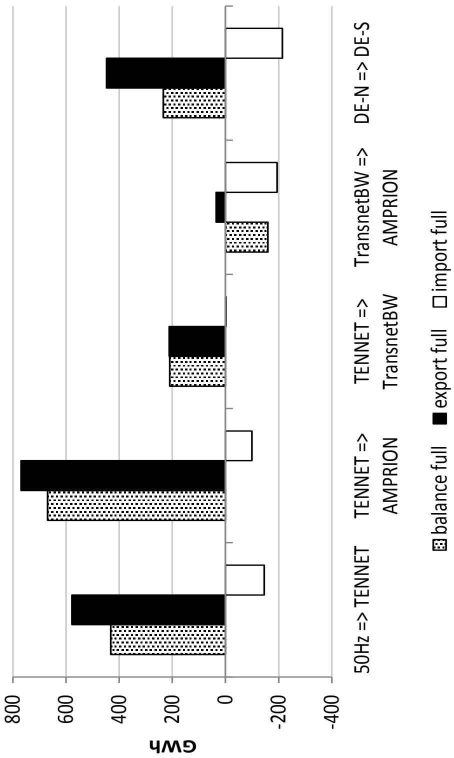


Figure A.18: Exchange CE, W27, *res*

Figure A.19: Exchange DE, W27, *full*



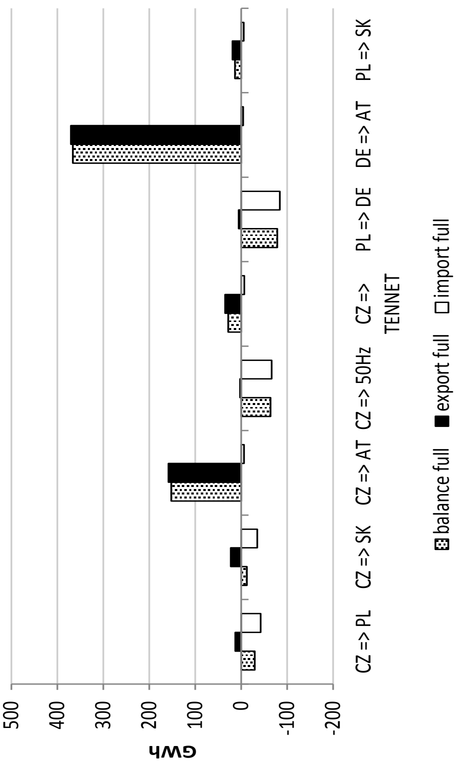


Figure A.20: Exchange CE, W27, *full*

Figure A.21: Analytical summary, W27

		Substations	Bujakow-Lískovec	Lískovec-Kopanina	Wielopole-Nošovice	Albrechtice-Dobrzeń	Varín-Nošovice	Slavětice-Dürnrohr	Sokolnice-Stupava	Sokolnice-Křižovany	Sokolnice-Bisamberg	Považská Bystrica-Lískovec	Senica-sokolnice	Hradec II-Etzenricht	Hradec I-Röhrsdorf	Přeštice-Etzenricht	Lemešany-Krosno Iskrzynia
		Interconnector	PL=>CZ	CZ=>PL	PL=>CZ	CZ=>PL	SK=>CZ	CZ=>AT	CZ=>SK	CZ=>SK	CZ=>AT	SK=>CZ	SK=>CZ	CZ=>Tennet	CZ=>50Hert	CZ=>Tennet	PL=>SK
		thermal limit	490	490	1700	1700	1700	3400	1700	1700	980	490	490	1700	3400	1700	3400
		linka	line138	line139	line155	line156	line523	line536	line537	line541	line571	line585	line586	line1179	line1180	line1181	line395
w27	base	average, MWh	28,765098	37,504682	119,30617	69,238186	82,6313	590,92694	96,165152	109,77836	279,96808	26,018123	23,442219	119,76256	275,64371	124,12867	118,3115
w27	base	average, %	5,87%	7,65%	7,02%	4,07%	4,86%	17,38%	5,66%	6,46%	28,57%	5,31%	4,78%	7,04%	8,11%	7,30%	3,48%
w27	base	min	-58,40548	-146,729	-219,2487	-276,8012	-662,2244	-547,342	-211,1892	-236,5046	-243,0523	-104,7512	-135,4217	-232,3169	-1061,605	-228,0176	-178,5265
w27	base	max	113,73985	72,003046	439,87912	117,65093	130,92594	1429,2487	798,62725	648,24672	646,59246	69,211441	49,704324	326,77335	1069,834	321,01021	766,63656
w27	base	st. Dev	27,478257	35,290619	107,67335	61,753047	97,844723	425,54585	122,21543	110,37404	195,59263	34,866805	23,208585	100,30204	290,40668	100,85991	121,74061
w27	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w27	res	average, MWh	35,829073	43,791766	137,13863	74,666255	83,819334	630,8159	87,163104	103,14691	300,63278	25,602283	22,011827	115,87535	357,46571	116,28003	131,85562
w27	res	average, %	7,31%	8,94%	8,07%	4,39%	4,93%	18,55%	5,13%	6,07%	30,68%	5,22%	4,49%	6,82%	10,51%	6,84%	3,88%
w27	res	min	-217,3056	-143,9847	-792,0434	-244,7199	-695,1595	-674,8803	-197,5251	-226,824	-348,9726	-106,4434	-143,4284	-333,4203	-1230,362	-345,0738	-786,7458
w27	res	max	109,72941	264,18821	416,04618	373,12902	320,37378	1353,8508	852,82289	688,20275	629,49141	84,307789	47,669834	409,56719	748,67201	423,69561	710,95594
w27	res	st. dev	46,360974	53,417411	164,35716	81,132321	88,882127	436,67531	100,93371	102,00625	202,04963	34,285665	21,404768	119,92967	294,79006	119,69041	162,36168
w27	res	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w27	full	average, MWh	38,40031	48,161039	156,06649	86,02744	94,663551	664,45168	90,957394	108,28918	314,07266	26,943835	23,02441	123,82573	405,98043	123,99406	143,76803
w27	full	average, %	7,84%	9,83%	9,18%	5,06%	5,57%	19,54%	5,35%	6,37%	32,05%	5,50%	4,70%	7,28%	11,94%	7,29%	4,23%
w27	full	min	-243,1181	-137,8836	-609,4437	-321,1577	-779,2019	-594,3853	-215,8584	-235,2959	-244,3536	-151,1151	-144,4783	-309,2187	-1772,276	-301,8664	-686,7611
w27	full	max	106,89649	187,75499	399,66265	261,23391	241,62113	1383,3531	803,81328	687,46094	588,25219	68,144825	49,450316	352,96238	866,21607	356,98464	511,05313
w27	full	st. dev	48,22377	56,137243	177,92017	89,376912	98,088862	420,66477	99,193203	100,89326	188,18581	35,730679	21,14689	122,61361	315,89048	122,37212	161,06735
w27	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w27	res	Δ avg load, %	1,44%	1,28%	1,05%	0,32%	0,07%	1,17%	-0,53%	-0,39%	2,11%	-0,08%	-0,29%	-0,23%	2,41%	-0,46%	0,40%
w27	full	Δ avg load, %	1,97%	2,17%	2,16%	0,99%	0,71%	2,16%	-0,31%	-0,09%	3,48%	0,19%	-0,09%	0,24%	3,83%	-0,01%	0,75%
w27	res	Δst. dev, %	68,72%	51,36%	52,64%	31,38%	-9,16%	2,62%	-17,41%	-7,58%	3,30%	-1,67%	-7,77%	19,57%	1,51%	18,67%	33,37%
w27	full	Δst. dev, %	75,50%	59,07%	65,24%	44,73%	0,25%	-1,15%	-18,84%	-8,59%	-3,79%	2,48%	-8,88%	22,24%	8,78%	21,33%	32,30%

		Substations	Aux-Oberbayern-Bürs	Vöhringen West-Bürs	Bürs-Obermorrweiler	Obermorrweiler-Bürs	Pirach-Sankt Peter	Altheim-Sankt Peter	Simbach-Sankt Peter	Pleinting-Sankt Peter	Leupolz-Westtirol	Leupolz-Westtirol	Bürs-Grünkraut	Pleinting-Sankt Peter	Sankt Peter-Pirach	Mikulowa-Neuerbau	Krajnik-Vierraden
		Interconnector	DE=>AT	DE=>AT	AT=>DE	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	AT=>DE	DE=>AT	AT=>DE	PL=>DE	PL=>DE
		thermal limit	980	490	1700	1700	490	490	490	490	490	1700	490	490	490	3400	980
		linka	line1166	line1167	line1168	line1169	line1170	line1171	line1172	line1173	line1174	line1175	line1176	line1177	line1178	line1206	line1207
w27	base	average, MWh	312,57132	106,74642	141,90345	149,45494	58,584439	69,162324	142,09591	82,741817	112,49218	416,62923	64,839618	83,620349	60,682373	141,41999	124,26682
w27	base	average, %	31,90%	21,78%	8,35%	8,79%	11,96%	14,11%	29,00%	16,89%	22,96%	24,51%	13,23%	17,07%	12,38%	4,16%	12,68%
w27	base	min	-140,4885	-58,18086	-429,8877	-124,2305	-57,44465	-59,43572	-59,32705	-85,56068	-49,0457	-181,647	-214,9255	-86,46914	-195,3431	-1108,636	-591,5135
w27	base	max	782,71201	297,19588	117,95355	452,7645	188,5896	261,31235	392	387,88157	283,07576	1048,4075	73,66324	392	59,501765	471,14878	252,66708
w27	base	st. dev	248,64248	95,557535	142,78088	150,37905	65,806897	68,347344	137,67877	102,77069	88,54723	327,94605	72,519728	103,86189	68,16347	204,54881	125,1539
w27	base	# extrems	5	0	0	0	0	0	10	6	0	0	0	6	0	0	0
w27	res	average, MWh	328,59127	133,54302	171,75451	180,89454	78,685102	95,301426	168,33177	116,43488	135,81849	503,02125	74,821413	117,67116	81,502849	214,2389	229,15488
w27	res	average, %	33,53%	27,25%	10,10%	10,64%	16,06%	19,45%	34,35%	23,76%	27,72%	29,59%	15,27%	24,01%	16,63%	6,30%	23,38%
w27	res	min	-130,8576	-54,46806	-558,3271	-97,06113	-136,9679	-13,38626	-12,81945	-152,6239	-42,36423	-156,9014	-292,6555	-154,2445	-269,6592	-1468,313	-784
w27	res	max	776,52703	332,22218	92,156937	588,03881	260,33647	298,12431	392	387,88157	309,83277	1147,5055	92,228048	392	141,87276	263,00656	63,425068
w27	res	st. Dev	242,86491	113,66457	162,20378	170,83556	88,173985	89,150184	150,13956	133,53223	102,55437	379,8233	80,73621	134,95004	91,331533	291,40433	179,96524
w27	res	# extrems	4	0	0	0	0	0	28	14	0	0	0	16	0	0	3
w27	full	average, MWh	335,24807	136,97499	165,5072	174,31477	64,000688	101,83711	186,3755	132,23353	141,14924	522,76435	68,644368	133,63755	66,292579	297,82843	234,96462
w27	full	average, %	34,21%	27,95%	9,74%	10,25%	13,06%	20,78%	38,04%	26,99%	28,81%	30,75%	14,01%	27,27%	13,53%	8,76%	23,98%
w27	full	min	-134,2284	-40,4709	-513,1569	-60,79066	-78,99646	-18,34105	-18,15274	-41,24909	-42,73303	-158,2673	-263,3956	-41,68707	-266,5416	-2076,081	-784
w27	full	max	780,16719	316,63929	57,719101	540,46487	257,32661	311,02907	392	387,88157	306,33642	1134,5563	49,75583	392	81,825357	298,2512	74,813204
w27	full	st. dev	222,76092	105,40128	143,01941	150,63028	77,070005	91,846452	160,06651	135,98218	96,157415	356,13135	69,781269	137,426	79,829915	452,16579	187,17195
w27	full	# extrems	3	0	0	0	0	0	44	17	0	0	0	18	0	0	5
w27	res	Δ avg load, %	1,63%	5,47%	1,76%	1,85%	4,10%	5,33%	5,35%	6,88%	4,76%	5,08%	2,04%	6,95%	4,25%	2,14%	10,70%
w27	full	Δ avg load, %	2,31%	6,17%	1,39%	1,46%	1,11%	6,67%	9,04%	10,10%	5,85%	6,24%	0,78%	10,21%	1,14%	4,60%	11,30%
w27	res	Δst. dev, %	-2,32%	18,95%	13,60%	13,60%	33,99%	30,44%	9,05%	29,93%	15,82%	15,82%	11,33%	29,93%	33,99%	42,46%	43,80%
w27	full	Δst. dev, %	-10,41%	10,30%	0,17%	0,17%	17,12%	34,38%	16,26%	32,32%	8,59%	8,59%	-3,78%	32,32%	17,12%	121,06%	49,55%

Figure A.22: Exchange DE, W49, *base*

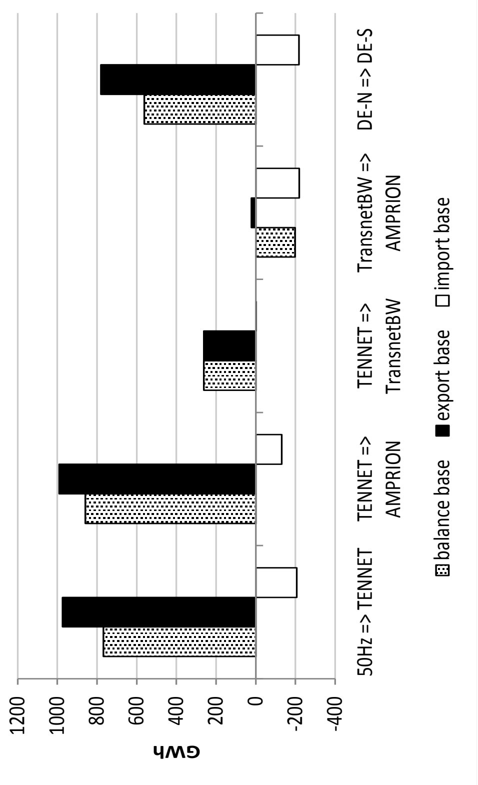
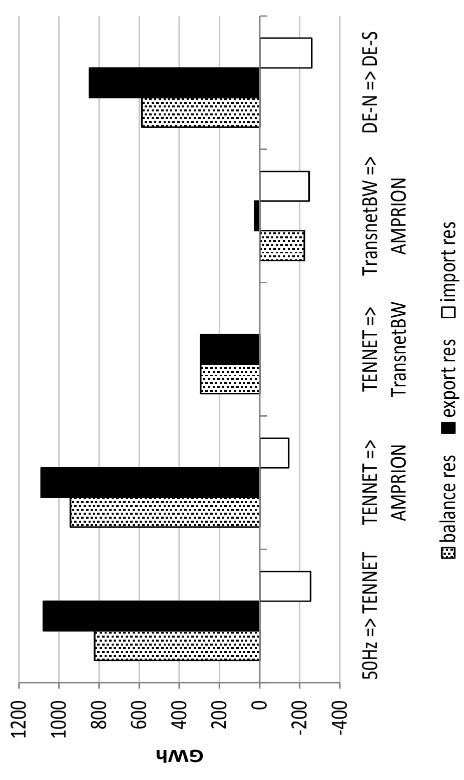


Figure A.23: Exchange DE, W49, *res*



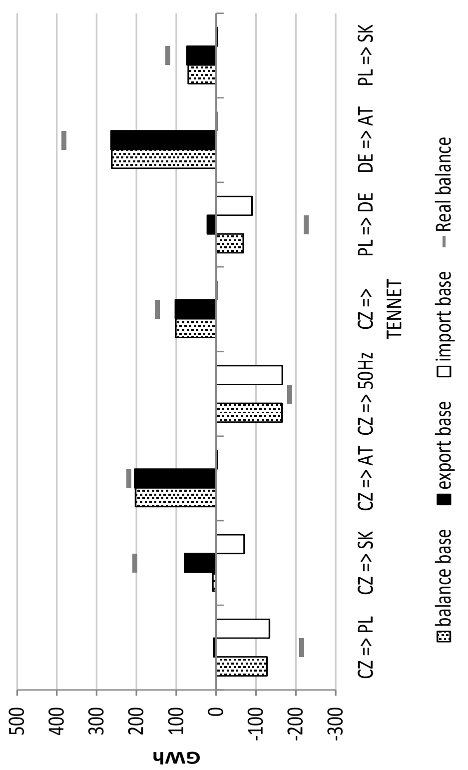


Figure A.24: Exchange CE, W49, *base*

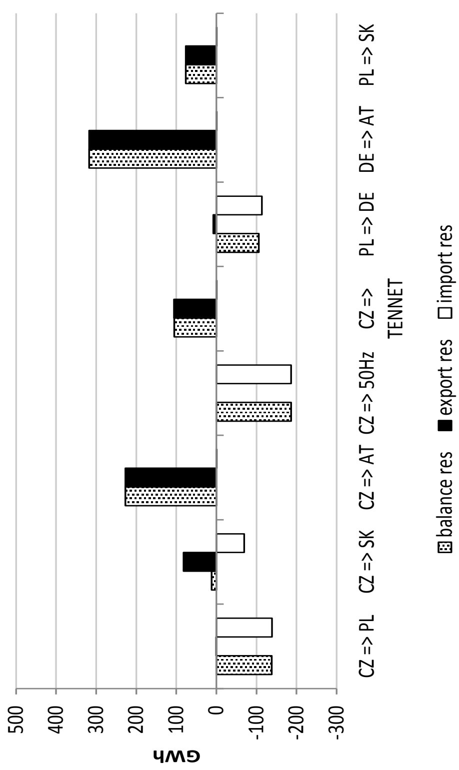
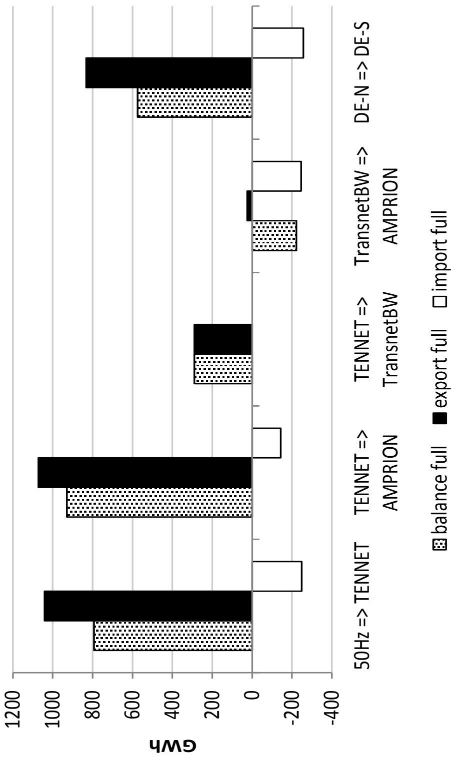


Figure A.25: Exchange CE, W49, *res*

Figure A.26: Exchange DE, W49, *full*



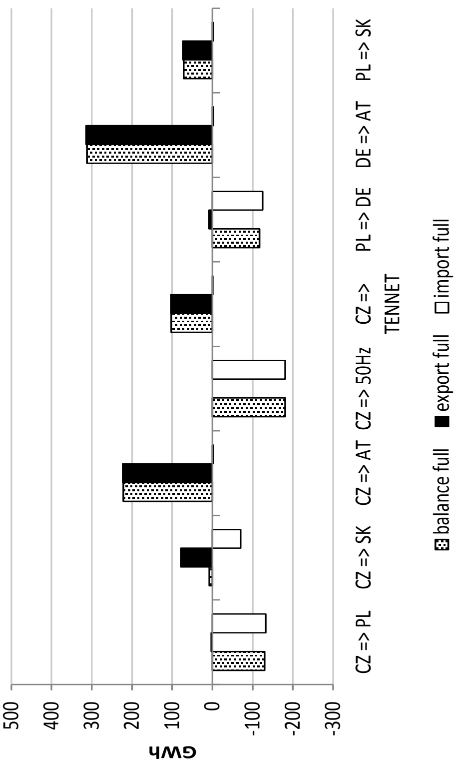


Figure A.27: Exchange CE, W49, *full*

Figure A.28: Analytical summary, W49

		Substations	Bujakow-Lískovec	Lískovec-Kopanina	Wielopole-Nošovice	Albrechtice-Dobrzeń	Varín-Nošovice	Slavětice-Dürnrohr	Sokolnice-Stupava	Sokolnice-Křižovany	Sokolnice-Bisamberg	Považská Bystrica-Lískovec	Senica-sokolnice	Hradec II-Etzenricht	Hradec I-Röhrsdorf	Přeštice-Etzenricht	Lemešany-Krosno Iskrzynia
		Interconnector	PL=>CZ	CZ=>PL	PL=>CZ	CZ=>PL	SK=>CZ	CZ=>AT	CZ=>SK	CZ=>SK	CZ=>AT	SK=>CZ	SK=>CZ	CZ=>Tennet	CZ=>50Hert	CZ=>Tennet	PL=>SK
		thermal limit	490	490	1700	1700	1700	3400	1700	1700	980	490	490	1700	3400	1700	3400
		linka	line138	line139	line155	line156	line523	line536	line537	line541	line571	line585	line586	line1179	line1180	line1181	line395
w49	base	average, MWh	95,668578	119,60452	400,26508	216,38643	258,53467	839,63397	253,31103	261,72377	389,55915	56,927069	55,039343	312,95245	995,86759	304,87182	453,05035
w49	base	average, %	19,52%	24,41%	23,55%	12,73%	15,21%	24,70%	14,90%	15,40%	39,75%	11,62%	11,23%	18,41%	29,29%	17,93%	13,33%
w49	base	min	-242,6806	-205,5211	-582,9566	-461,1891	-998,1391	-484,482	-340,5051	-391,659	-213,7181	-235,3341	-120,2269	-146,8006	-1935,51	-169,6429	-543,5561
w49	base	max	157,0908	182,385	759,61082	124,04302	109,1745	1365,928	772,80906	573,12897	632,32218	123,99276	82,771091	501,59318	684,09544	495,58368	1312,98
w49	base	st. Dev	66,241916	68,280465	233,51309	108,78336	230,45803	372,84121	287,32483	250,97747	174,68593	66,503137	52,73464	130,06701	380,99238	133,77689	315,65506
w49	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w49	res	average, MWh	90,669622	117,43048	394,8018	225,36978	277,3222	921,14721	253,03737	260,15787	429,96965	57,00616	55,213842	320,18939	1110,8394	307,95431	455,78569
w49	res	average, %	18,50%	23,97%	23,22%	13,26%	16,31%	27,09%	14,88%	15,30%	43,87%	11,63%	11,27%	18,83%	32,67%	18,11%	13,41%
w49	res	min	-38,41084	-221,72	-8,79483	-484,6356	-988,9488	-90,85198	-326,667	-376,3597	-29,98491	-267,8732	-122,7652	-51,18431	-2024,733	-55,19701	-102,2964
w49	res	max	166,11902	59,623232	779,15939	-15,14295	-21,67557	1457,0077	781,18762	584,22638	668,86322	129,9324	79,555752	490,11784	-162,2374	486,48542	1266,4258
w49	res	st. dev	39,334469	43,675343	157,73722	90,684554	235,52658	290,18967	297,326	249,31758	134,89314	65,303754	53,15864	100,06919	326,63662	103,78117	282,90437
w49	res	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w49	full	average, MWh	90,206933	115,66864	385,35783	214,84399	261,03633	908,54021	252,0121	259,78308	423,86989	55,725381	54,650128	313,00605	1075,1886	302,07114	444,35185
w49	full	average, %	18,41%	23,61%	22,67%	12,64%	15,36%	26,72%	14,82%	15,28%	43,25%	11,37%	11,15%	18,41%	31,62%	17,77%	13,07%
w49	full	min	-172,5121	-202,3998	-490,5451	-445,9084	-987,0484	-508,4266	-344,8833	-391,0405	-218,8468	-221,5846	-140,8455	-173,3656	-2000,353	-199,2661	-358,8975
w49	full	max	153,92565	134,21251	737,94683	104,75325	106,46211	1387,6083	907,53737	671,25707	640,10182	134,88355	82,701181	556,41167	-214,4497	551,48748	1257,068
w49	full	st. dev	48,657172	55,520916	185,6687	98,970284	230,55896	323,81271	294,80503	250,88482	153,32638	65,910942	52,733475	113,59406	320,69182	117,14047	292,51134
w49	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

w49	res	Δ avg load, %	-1,02%	-0,44%	-0,32%	0,53%	1,11%	2,40%	-0,02%	-0,09%	4,12%	0,02%	0,04%	0,43%	3,38%	0,18%	0,08%
w49	full	Δ avg load, %	-1,11%	-0,80%	-0,88%	-0,09%	0,15%	2,03%	-0,08%	-0,11%	3,50%	-0,25%	-0,08%	0,00%	2,33%	-0,16%	-0,26%
w49	res	Δst. dev, %	-40,62%	-36,04%	-32,45%	-16,64%	2,20%	-22,17%	3,48%	-0,66%	-22,78%	-1,80%	0,80%	-23,06%	-14,27%	-22,42%	-10,38%
w49	full	Δst. dev, %	-26,55%	-18,69%	-20,49%	-9,02%	0,04%	-13,15%	2,60%	-0,04%	-12,23%	-0,89%	0,00%	-12,66%	-15,83%	-12,44%	-7,33%

		Substations	Aux-Oberbayern-Bürs	Vöhringen West-Bürs	Bürs-Obermorrweiler	Obermorrweiler-Bürs	Pirach-Sankt Peter	Altheim-Sankt Peter	Simbach-Sankt Peter	Pleinting-Sankt Peter	Leupolz-Westtirol	Leupolz-Westtirol	Bürs-Grünkraut	Pleinting-Sankt Peter	Sankt Peter-Pirach	Mikulowa-Neuerbau	Krajnik-Vierraden
		Interconnector	DE=>AT	DE=>AT	AT=>DE	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	DE=>AT	AT=>DE	DE=>AT	AT=>DE	PL=>DE	PL=>DE
		thermal limit	980	490	1700	1700	490	490	490	490	490	1700	490	490	490	3400	980
		linka	line1166	line1167	line1168	line1169	line1170	line1171	line1172	line1173	line1174	line1175	line1176	line1177	line1178	line1206	line1207
w49	base	average, MWh	302,24328	108,73012	147,22731	155,06211	7,997353	57,137395	70,591001	63,164282	112,73136	417,5151	63,901953	63,834944	8,2837416	272,8595	390,68329
w49	base	average, %	30,84%	22,19%	8,66%	9,12%	1,63%	11,66%	14,41%	12,89%	23,01%	24,56%	13,04%	13,03%	1,69%	8,03%	39,87%
w49	base	min	-133,5568	-67,3692	-300,9372	-112,7176	1,0201495	-5,635156	-3,908095	-73,50857	-95,42845	-353,4315	-144,8228	-74,28907	-64,91128	-1540,763	-784
w49	base	max	560,5513	203,16363	107,02235	316,95181	62,667138	130,08703	211,64117	197,94007	196,96511	729,48561	53,01738	200,04175	-1,056681	700,78388	108,1234
w49	base	st. dev	98,679397	34,610264	61,565264	64,841498	12,39671	22,911774	37,502844	43,592026	35,802364	132,59866	37,470616	44,054875	12,840642	390,27963	228,59407
w49	base	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
w49	res	average, MWh	349,29671	129,81162	177,59067	187,04127	11,123933	71,828884	90,301704	80,587523	132,32316	490,07583	78,290032	81,443181	11,522286	188,48198	536,44128
w49	res	average, %	35,64%	26,49%	10,45%	11,00%	2,27%	14,66%	18,43%	16,45%	27,00%	28,83%	15,98%	16,62%	2,35%	5,54%	54,74%
w49	res	min	33,068696	20,754606	-335,6114	6,0700276	1,5067021	19,928559	21,311629	-8,354308	20,77541	76,944403	-163,8735	-8,443012	-88,82246	-1500,246	-784
w49	res	max	577,0603	210,96196	-5,763328	353,47122	85,751656	171,96309	330,04035	254,34608	212,67012	787,65114	57,587193	257,04666	-1,560658	446,57235	-87,62015
w49	res	st. Dev	85,93507	29,270496	58,729944	61,855295	16,90785	25,061317	50,137009	45,734415	28,455466	105,38847	38,315391	46,220011	17,513328	267,13158	185,22136
w49	res	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
w49	full	average, MWh	344,2349	128,05823	178,65617	188,16347	11,583036	71,245458	89,711445	81,336104	130,36722	482,83175	79,390004	82,199711	11,99783	239,02343	553,43695
w49	full	average, %	35,13%	26,13%	10,51%	11,07%	2,36%	14,54%	18,31%	16,60%	26,61%	28,40%	16,20%	16,78%	2,45%	7,03%	56,47%
w49	full	min	-376,5921	-97,64942	-344,3376	-146,9118	-79,15631	19,243352	21,647733	-155,2103	-131,3011	-486,2906	-168,8381	-156,8583	-88,82246	-1723,36	-784
w49	full	max	586,15386	217,20006	139,48881	362,66171	85,751656	172,5271	330,61098	256,25506	215,09824	796,64397	62,855322	258,97591	81,990935	421,91641	0,7160512
w49	full	st. dev	105,69671	35,467339	62,681688	66,017334	18,274312	23,735005	48,856038	46,65254	36,218508	134,1399	37,773635	47,147885	18,928723	341,06688	191,92962
w49	full	# extrems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49

w49	res	Δ avg load, %	4,80%	4,30%	1,79%	1,88%	0,64%	3,00%	4,02%	3,56%	4,00%	4,27%	2,94%	3,59%	0,66%	-2,48%	14,87%
w49	full	Δ avg load, %	4,28%	3,94%	1,85%	1,95%	0,73%	2,88%	3,90%	3,71%	3,60%	3,84%	3,16%	3,75%	0,76%	-1,00%	16,61%
w49	res	Δst. dev, %	-12,91%	-15,43%	-4,61%	-4,61%	36,39%	9,38%	33,69%	4,91%	-20,52%	-20,52%	2,25%	4,91%	36,39%	-31,55%	-18,97%
w49	full	Δst. dev, %	7,11%	2,48%	1,81%	1,81%	47,41%	3,59%	30,27%	7,02%	1,16%	1,16%	0,81%	7,02%	47,41%	-12,61%	-16,04%

Figure A.29: Transmission CE W4

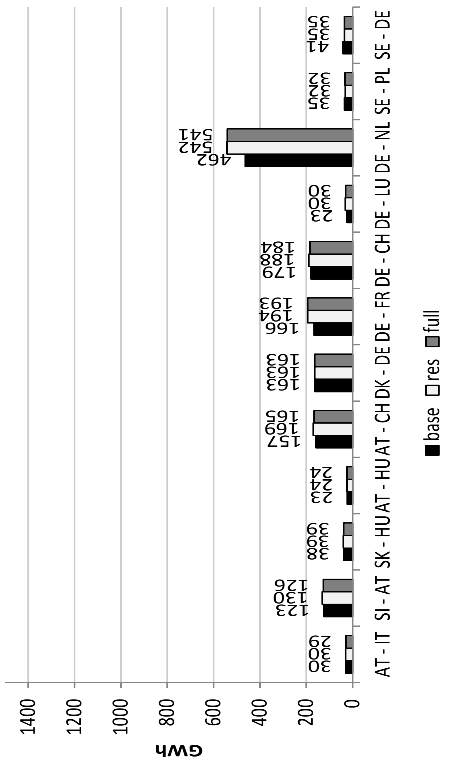
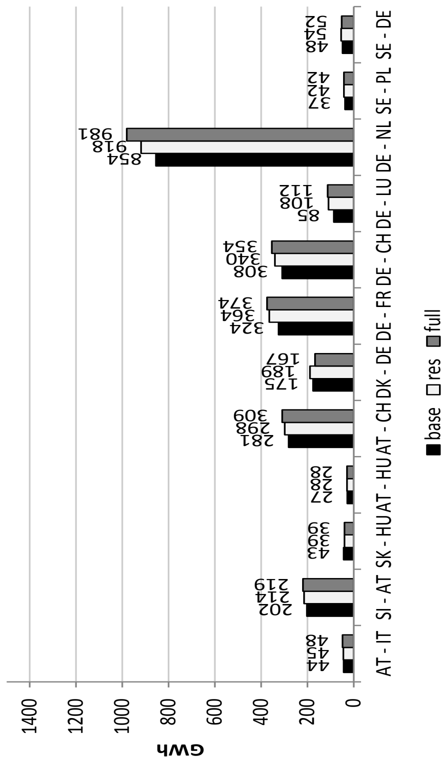


Figure A.30: Transmission CE, W27



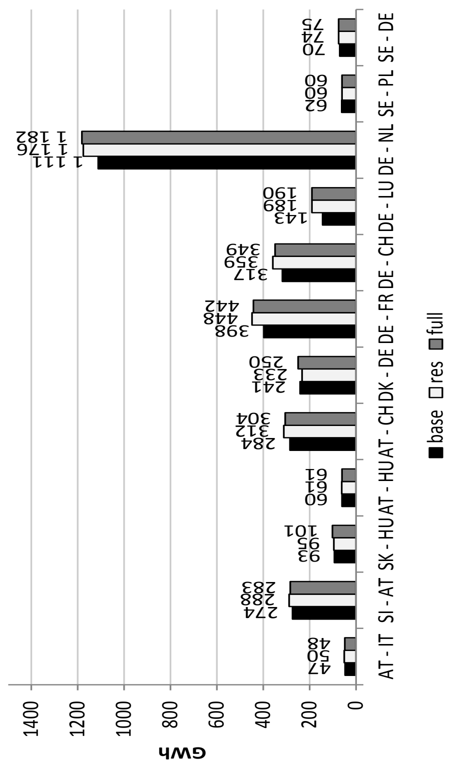


Figure A.31: Transmission CE, W14

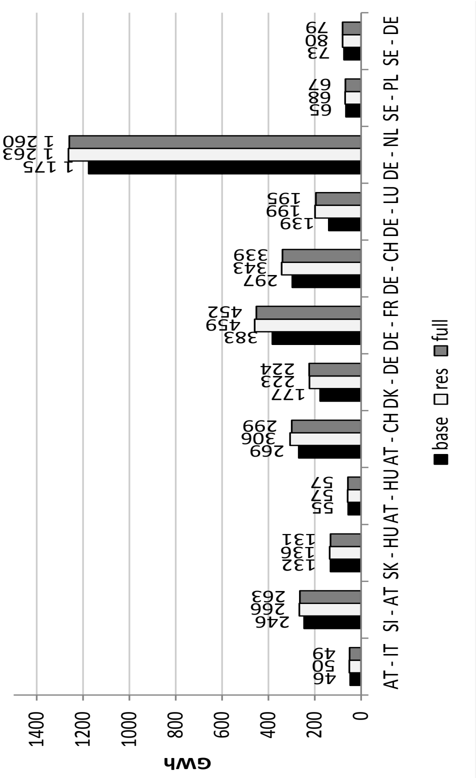


Figure A.32: Transmission CE, W49