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# WIND POWER EXPANSION IN AUSTRIA: EFFECTS ON THE BALANCING OF REGIONAL ELECTRICITY SUPPLY AND DEMAND

BY

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# ABSTRACT

In recent years, wind power has been the fastest growing renewable energy source in Austria as well as in other European countries and is expected to account for a major share of the newly installed renewable capacities until 2020. Due to the stochastic nature of wind, there are concerns about how to integrate large amounts of intermittent electricity generation into the electrical system as it may decrease the reliability of the power grid.

The objective of this thesis is to assess the potential of reducing the strain on the power grid by optimally deploying wind turbines in Austria. The analysis takes into account the spatial distribution of both, potential wind power production and electricity consumption. Therefore, the residual load is analyzed, which is occurring from potential wind power expansions in Austria.

Results indicate that if wind farm planning would consider the regional electricity consumption, the supra-regional electricity flow can be significantly reduced at little extra costs and therefore, may reduce the strain on the transmission power grid. However, the diversification of the location of wind power plants is not incentivized by the current subsidy system, i.e. feed-in tariffs. This is a serious flaw in the current subsidy system, which thus should be carefully examined and revised.

# KURZFASSUNG


Windkraft ist die in den letzten Jahren am schnellsten wachsende, erneuerbare Energiequelle – in Österreich ebenso wie in der Europäischen Union. Es wird erwartet, dass sie einen Hauptanteil der neu installierten Leistungen aus erneuerbarer Energie bis 2020 aus macht. Dennoch gibt es Bedenken, dass durch die Unstetigkeit des Windes und der daraus folgenden unregelmäßigen Stromerzeugung, eine Einspeisung von großen Strommengen aus Windkraft in das Energiesystem die Stabilität und Zuverlässigkeit des Stromnetzes beeinträchtigen könnte.

Ziel dieser Arbeit ist es herauszufinden, ob sich die Belastung des Stromnetzes durch eine optimierte, österreichweite Standortwahl von Windkraftwerken verringern lässt, indem die lokale Verteilung der potenziellen Windkraftstandorte ebenso wie der regionale Stromverbrauch berücksichtigt wird. Zu diesem Zweck wurde eine räumliche und zeitliche Analyse der Residuallasten, die aus einer potenziellen Windkrafterweiterung resultieren würde, durchgeführt.

Die Ergebnisse lassen erkennen, dass sich die überregionalen Stromflüsse signifikant reduzieren lassen, wenn bei der Planung eines Windparks der regionale Stromverbrauch berücksichtigt würde. Mit nur geringen zusätzlichen Kosten könnte dadurch die Belastung auf das Übertragungs-Stromnetz verringert werden. Trotz dieser Erkenntnis ist die räumliche Verteilung von Windkraftwerken im derzeitigen Fördersystem, mit garantiertem Einspeisetarif, nicht vorgesehen. Dieser erhebliche Mangel im Fördersystem für erneuerbare Energien sollte sorgfältig überprüft und gegebenenfalls überarbeitet werden.

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# 1. INTRODUCTION

European economies heavily depend on electricity. The current economic and financial crisis is curbing the growing demand for electricity, but this may not be permanent. A large proportion of electricity is still generated from fossil fuels contributing to a third of all carbon emissions in Europe. With the mounting worries about climate change, measures are implemented to reduce carbon dioxide emissions, in order to promote energy from renewable sources and to increase energy efficiency (Boccard 2010).

The European Commission brought forward the EU directive 2009/28/EC including the policy to reduce 20% of carbon emissions and increase the share of total final energy consumption from renewable energy sources to 20% until 2020. The power sector will likely carry a disproportional share of the burden to reach the 20% target because of the limited scope for deployment of renewables in other sectors of energy production and use. Therefore, the share of renewables in the European electricity production mix will need to be increased from 30 to 40% (Roques, Hiroux, and Saguan 2010). To achieve the overall European target, every country has to establish national renewable energy action plans. Austria set its target to produce 34% of the total final energy consumption from renewable energy sources (Gass et al. 2013).

In the recent years, wind power has been the fastest growing renewable energy source in Europe and is expected to account for a major share of the newly installed renewable capacities till 2020 (Roques, Hiroux, and Saguan 2010). However, there are concerns to integrate large amounts of intermittent electricity generation into the electrical system as it may decrease the reliability of the power grid (Denholm et al. 2010). The stochastic nature of wind and the lack of efficient storing facilities of electricity are the main challenges in wind energy production. According to Havranek (2012), a high share of wind power in the energy mix and therefore an unsteady energy production can stress the power grid and actions are needed to be taken. In Austria, wind power is also the fastest growing renewable energy source, increasing its installed capacity by 30% in the year of 2012 only. The majority of wind power capacities are located in Burgenland and Lower Austria. With a potential growth of wind power output from the current production level of 2.9 TWh up to 7.3 TWh in 2020 (Hantsch and Moidl 2007) and the expectation that newly installed capacity will also be located in the northeastern parts of the country, severe stress may be created for the power grid (“IG Windkraft” 2014; Wolter and Rendel 2011).

A way to smoothen wind power production would be to optimally locate wind farms across different geographical areas. However, power plant investors are considering private costs and revenues of their investments and the diversification of the location of wind power plants (WPP) is not incentivized by the current subsidy scheme, i.e. national fixed feed-in tariffs. E.g. investors in wind parks do not bear costs of upgrading the power grid system caused by spatially concentrated deployment of wind power, which therefore may be considered as an externality of wind power production (Borggrefe and Nüßler 2009; Degeilh and Singh 2011).

Therefore, regionally concentrated wind power deployment, as observed in the current Austrian expansion, may be suboptimal from the perspective of the entire electricity system. This thesis assesses the potential of reducing the strain on the transmission grid by optimally deploying wind turbines in Austria. For this purpose, demand and wind power supply is balanced at regional level.

## 1.1. AIM OF THE THESIS

The aim of this thesis is to elaborate the extent to which wind power can be expanded in Austria without the need of a significant upgrade of the transmission power grid. By selecting wind power plant locations in order to reduce the regional residual flow, i.e. the difference between regional power load and wind power production, the need for electricity flows is minimized in the national transmission system. However, electrical effects in the power grid are not examined but limit the analysis to identify locations in Austria where wind power can be expanded without significantly increasing residual flows.

To analyze the regional energy balance and calculate the residual flows, Austria is divided into regions using substations which act as power node proxies for each region. Gass et al. (2013) identified potential wind power sites in Austria and Schmidt et al. (2013) generated time series of wind speeds and power outputs for 79 aggregated sites. The electricity load was modeled by Zeyringer und Simoes (2013) and is adapted for this work. The residual load is calculated by locally aggregating the energy production and consumption. Regions are identified where production would lead to an electricity surplus or where the produced power would be completely consumed locally. The optimal allocation and quantity of installed turbines per region is assessed with an optimization model.

## 1.2. OUTLINE OF THE THESIS

The thesis is divided into four consecutive chapters starting with chapter 2 which contains a literature review on wind power utilization in Austria. First, the historic development is described followed by an outline of the situation today. The future of the Austrian wind power generation is presented by several studies regarding the potential of wind power. Furthermore, basic principles of electricity production and consumption are described and possible ways of integrating renewable energy sources into the power grid are discussed. Chapter 3 presents the data and methodology used for this thesis. Chapter 4 presents the results of the study. In the first part the division into regions is shown. Afterwards the scenario outcomes are presented. Chapter 5 provides a discussion of the results and presents final conclusions.

# 2. WIND POWER IN AUSTRIA

## 2.1. HISTORICAL DEVELOPMENT

After the Oil crisis in the 1970ies, major efforts were made by many governments to gain independence from fossil fuels. Mainly nuclear energy was promoted, but also renewable energy sources were researched as alternatives to oil and gas power. At this time, the efforts of state funded wind power research focused on small scale systems. Despite technical feasible solutions, there was no rapid success. Lower oil prices destroyed the market potentials, and a lack of large scale field trials caused a stagnation of wind power research in Austria in the mid 1980ies. In consequence, it was assumed that the physical wind potential for the installation of wind power plants (WPP) was not sufficient in Austria. In the late 1980ies, measurements of wind conditions proved that many sites in Austria, especially in Burgenland, have as good wind conditions as offshore sites, 15km distant from land, in Denmark or Germany ("IG Windkraft" 2014).

In 1994, the first subsidiary scheme was introduced for electricity produced with renewable energy sources. 30% of investment costs were funded by the Environmental Ministry and the existing feed-in tariff ("Verbundtarif") of 65 "Groschen" / kWh was doubled the first three years of operation. In the same year, the first relatively large wind power plant with a rated capacity of 150 kW was built in Marchfeld and followed by several other WPP in the next years (Nährer 2010).

The electricity law of 1998 guaranteed a fixed feed-in tariff for Eco-Power-Plants which was extended in the Eco-Electricity Act of 2002 („IG Windkraft" 2013). Until the change of the Eco-Electrical Act in 2006, the fixed feed-in tariffs and a secure investment environment led to a construction boom. The installed capacity was expanded from 415 MW in 2003 to 1,011 MW in 2010. According to Gass et al. (2013), the expansion of wind energy in Austria is closely related to the feed-in tariffs, which have been granted for a specific time after starting the operation of a wind turbine. After the amendment, the expansion slowed down due to lower feed-in tariffs. Fixed feed-in tariffs were only granted to facility operators who had contracts with the "Ökostromabwicklungsstelle" (OeMAG).

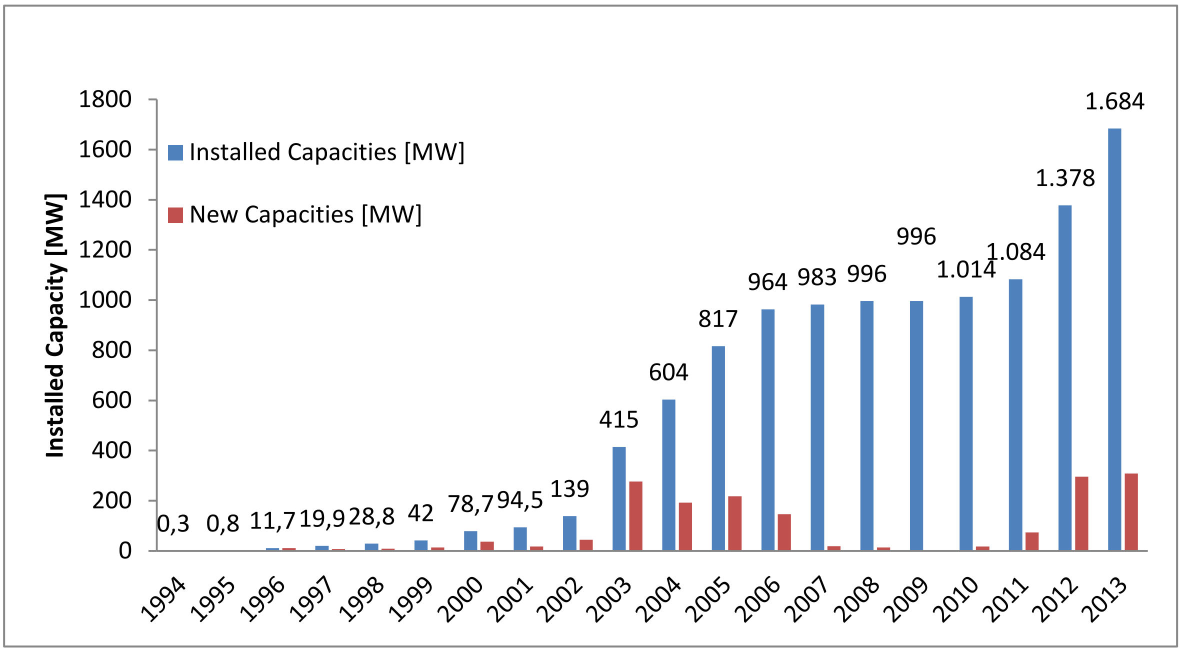



**Figure 1***: Installed and annually installed wind power capacity in Austria; Source: Graph created by author based on data by "IG Windkraft" (2013)*

The OeMAG has annually limited subsidies for new facilities and if the subsidies are used up, no further contracts are granted. Figure 1 shows that these regulations in combination with very low feed-in tariffs caused a stop in construction – with only few exceptions – of new WPP between the years 2007 and 2009 . Another major amendment to the Eco-Electricity Act in 2010 granted a fixed feed-in tariff of 9.7 ct/kWh, which led to better conditions for financing new WPP ("IG Windkraft" 2014).

## 2.2. State of Play

With a feed-in tariff of 9.5 ct/KWh in the year 2012, wind power facility operators find good conditions for implementing new projects. At present, 876 wind turbines with a total capacity of 1,684 MW of capacity are deployed in Austria. Favourable conditions are found in the northern and eastern parts of the country, particularly in the federal states of Burgenland and Lower Austria with 90% of the total installed capacity. The additionally installed wind power capacity of 295.65 MW in the year of 2012 – an increase of 30% – was the highest annual expansion in Austria so far. Major growth rates were also accomplished in Burgenland ("IG Windkraft" 2014) (Gass et al. 2013). Wind power in these regions is expected to further increase, therefore challenging the grid operators, in particular Bewag Netz GmbH and EVN Netz GmbH (Wolter and Rendel 2011).

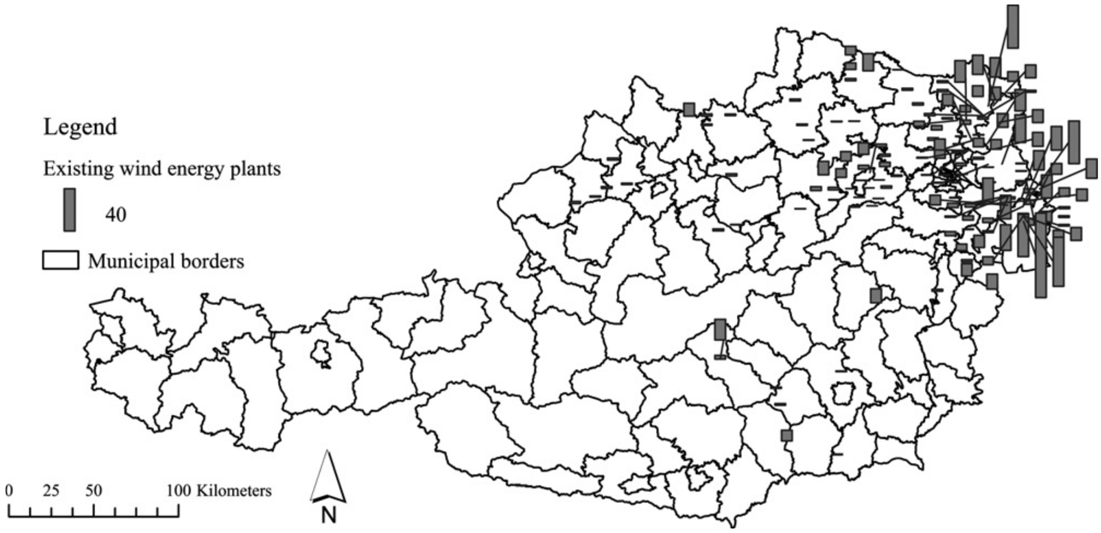



***Figure 2***: *Installed wind capacity in Austria; Source: Gass et al. (2013, 2)*

Figure 2 gives an overview of the location and quantity of installed wind turbines in Austria. Major production takes place in the East of Austria.

Wind power plants produce a total of about 2.9 TWh annually which represents about 5% of Austrian electricity consumption. Figure 3 shows the share of installed wind power capacity in the federal states of Austria. Promoted by the Eco-Electricity Act, the vast majority of new installed capacities are new plants since the repowering potential is negligible due to the low age and the high performance of the existing WPP (Wolter and Rendel 2011).

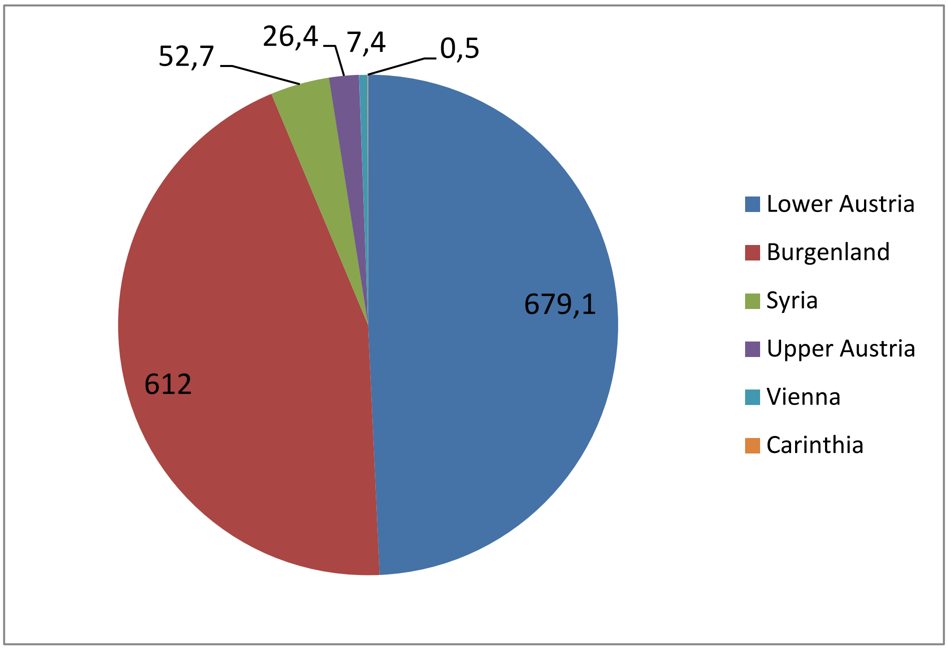



***Figure 3:*** *Wind power capacities in the federal states of Austrian in MW; Source: Graph created by author based on data by "IG Windkraft" (2013)*

## 2.3. WIND POWER POTENTIAL

The Austrian regional development plan distinguishes between technical and theoretical potentials. The theoretical potential mainly depends on the wind velocity. The technical potential includes the level of efficiency, accessibility and infrastructure as dominant factors. It is lower as the theoretical potential. Furthermore, the feasible potential is subject to restrictions like natural protection areas, laws, zoning plans and also the acceptance of the population (Wolter and Rendel 2011).

Image 4 shows a comparison between the theoretical and technical potential of wind power production in Austria (Prinz et al. 2009). It can be observed that almost the complete theoretical potential for wind power production in the northeast is considered to be a technical potential. Also in Upper Austria and in Styria both theoretical and technical potentials are almost identical. On the other hand there is a gap between theoretical and technical potential in Tyrol and Carinthia, which means that the theoretical wind power cannot be used for electricity production due to the topography of the Alps and their high elevations and steep slopes (Eicher 2012).

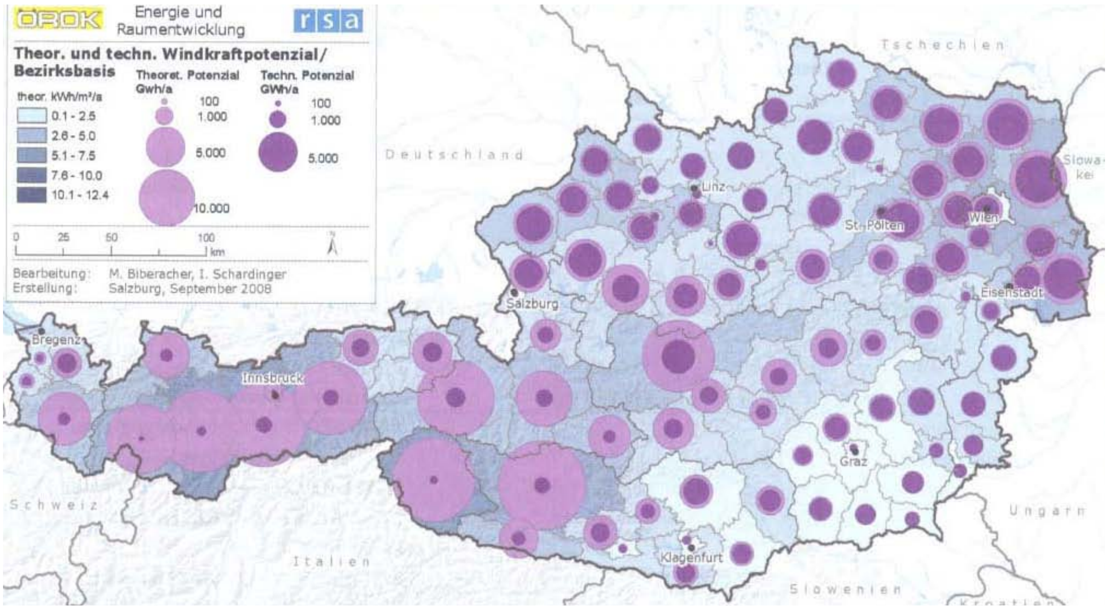


***Figure 4:*** *Theoretical and technical wind power potential in Austria; Source: Prinz et al. (2009, 45)*

The available studies about wind power potential for electrical production in Austria estimate annual production potentials between 3,000 GWh and 20,000 GWh. Most of the studies were made considering the current state of the art of the turbine technology. Technical improvements were practically never anticipated (Hantsch and Moidl 2007).

Prokorny (1981) published one of the first studies about the Austrian wind power potential. For his analysis, he identified areas with good wind conditions and homogeneously distributed state of the art WPP over it. The available technologies at that time were hub heights of 20 meters, rotor diameters of 15 meters and power output of 50 kW. He estimated a technical potential between 6,600 to 10,000 GWh per year. About 150,000 power plants would have been necessary to exploit this potential under these conditions.

Kury and Dobesch (1999) used 56 WPP in Lower Austria for their calculations of potential. Through regionally differing full load production, power yields of WPP were predicted. The installed turbines had an average power output of 1 MW and a rotor diameter of 55 meters. Regions like natural reserves, national parks, residential areas, military facilities and surface water were excluded from the approximations. The technical potential was estimated to be about 1,850 MW power output or 3,040 GWh per year for Austria.

In 2007, Reinhold Christian (Hantsch and Moidl 2007), in cooperation with EVN, examined the Austrian wind power potential. An approximation of the technically feasible and ecologically acceptable renewable energy potential was made. An annually wind power output between 5,500 and 7,000 GWh was estimated.

Further estimates of the wind power potential in Austria were conducted by Streicher et al. (2010). The focus of their study is the assessment of energy autarky of Austria by 2050. Some of the general assumptions in this study are:

- Austria produces 100% of its energy demand by renewable energy sources until 2050.
- The net-energy import in form of embodied energy will not increase.
- Cross-border trade in energy is permitted on daily and weekly bases but annual imports are equal to annual exports.
- Only domestic pumped hydro storage plants or chemical storages are available for storing electricity.

The maximum technical wind power potential was estimated to be 18 TW h per year according to the study. This corresponds to around 29% of the total Austrian net electricity production (without electricity imports) in 2006 (62.0 TWh). Due to technical restrictions (i.e. no sufficient storage and transmission capacities), a maximum of 13.9 TWh per year can be integrated into the power grid according to the study.

Stocker et al. (2011) analyzed the sustainable energy development in Austria until 2020. Possible economic and ecological effects of sustainable growth of electricity production were investigated together with stakeholders and experts in the field of energy technology and policy. With increasing technological wind power production know-how, the full-load hours are expected to rise in parallel with the installed capacity per m² due to rising plant sizes. A wind power potential of 22,235 TJ (6,176 TWh) is estimated until 2020.

In 2013, calculations were conducted by Groiß, Boxleitner, and Chochole (2013). They assessed the wind power potential in Austria by identifying potential areas and determining the potential installable capacity per area. Potential wind farms are restricted by the availability of land, excluding e.g. natural reserves, by accessibility to production sites and by economical considerations. The wind power production was calculated assuming 2 MW turbines, which in total produce 8 TWh per year in their scenario.

Table 1 shows a s ummary of the wind power potential analysis presented in this section. In the scenarios on w ind power expansion for Austria, presented in the empirical section of this thesis, the wind power expansion potentials are based on the estimates made by Streicher et al. (2010).

***Table 1:*** *Overview of wind power potential predictions; Source: Table created by the author*

| Author | Annual Power Production [TWh] | Issue Year | Target Year |
|---|---|---|---|
| **Prokorny (Hantsch and Moidl 2007)** | 6.6 - 10 | 1981 | max. |
| **Kury and Dobesch (1999)** | 3.04 | 1999 | max. |
| **Christian (Hantsch and Moidl 2007)** | 5.5 - 7 | 2007 | n.s. |
| **Streicher et al. (2010)** | 13.9 | 2010 | 2050 |
| **Stocker et al. (2011)** | 6.18 | 2011 | 2020 |
| **Groiß, Boxleitner & Chochole (2013)** | 8 | 2013 | n.s. |

*n.s. … not specified.*

*max. … Maximum of achievable potential without stating specific year.*

The vast difference of estimates indicates that there are major uncertainties, and that the estimates also depend on the focus of research of the respective study. Some studies assess the technical potential, whereas others are calculating an actual realizable wind power production for a certain due date – such as necessary for the 2020 targets (Hantsch and Moidl 2007).

Further uncertainties are, according to Gass et al. (2013), inaccurate wind resource estimations as well as limited economic assessments of the wind power potential. Technological progress is not or not sufficiently enough brought into account and optimal wind turbine sites are not assessed spatially explicitly.

## 2.4. Integration of Renewables into the Power Grid

### 2.4.1. Electricity Production and Consumption

The consumption of electrical energy undergoes variations depending on the time of day, day of the week and month. In graph 5, a typical daily load diagram is shown for the case of Germany – which has a similar climate and thus load profile as Austria - revealing the peak and minimum demand of a day in summer and winter (Schwab 2012). Factors such as the need for cooling, heating and light are responsible for the seasonal and daily patterns (Denholm et al. 2010).

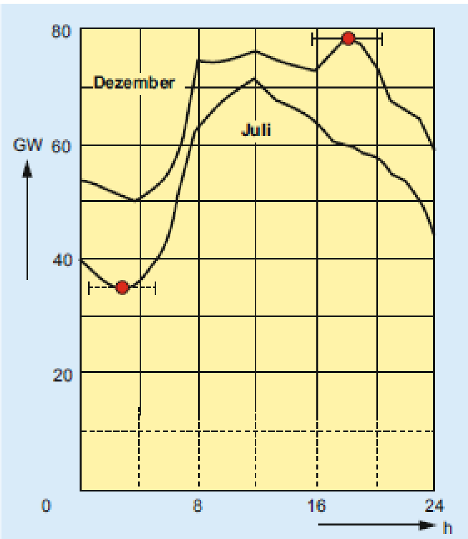



***Figure 5**: Load diagram; Source: Schwab (2012, 35)*

On average, the highest load occurs during a day in December and the lowest during a night in June. In days of minimal electricity consumption, more than half of the installed power plant capacity is out of operation. Storing electrical energy to a large extent is limited, so that at all times the consumption must be matched with power production. If the power balance is disturbed, a c hange in voltage and frequency of the nominal capacity would occur (Schwab 2012).

The grid operators have to predict variations of demand and supply to ensure a reliable power grid system. They have to dispatch back-up plants, in case of changes to the scheduled production system. Dalheimer (2011) distinguishes between base, intermediate and peak loads:

- The base load is a constant demand within 24 hours and it is commonly produced by coal fired, nuclear or run-of-the-river hydro power plants. The power output controlling abilities of these plants are of minor interest, the average cost of a produced kWh have priority. Since they have very cheap marginal cost for producing electricity, they are running on full load for almost all of the time.
- The intermediate load complies with the variations of the daily routine, since at night there is much less demand than during the day. This load is fairly good to plan and can be provided, for instance, with coal power plants.
- The peak load can also be planned but it is associated with many uncertainties. The peak demand is provided by starting up peak load power stations such as gas turbine or pumped storage hydro power plants. They can adapt their power output by up to 20% of their nominal capacity within a minute. Since the fuels for peak load power plants are more expensive than for base load power plants (e.g. gas vs. coal), they hardly work as base-load power plants.

### 2.4.2. Integrating Wind Power into the Power Grid

Prognoses for installed wind power in Europe estimates a doubling of the capacity from 80 GW in 2010 to 140-180 GW in 2015. However, there are technical limits to the integration of wind power because as the wind capacity increases, measures have to be taken to ensure that the intermittency of wind energy does not reduce the reliability of power systems (Ibrahim et al. 2011; Kranzl 2011).

The operation of electric power systems includes complex processes in forecasting the demand of electricity, and providing the required large number of power plants to meet the varying load. The intermittent power production with renewable energy sources is additionally aggravating the process for balancing supply and demand and can be very challenging for the power grid (Denholm et al. 2010; Havranek 2012). The availability of electricity from renewable energy sources like wind and solar energy is unsteady and in phases with strong winds, base load power plants need to shut down so that the energy produced with renewable sources can be used. It is not yet clear whether or not that is feasible in all cases. On the one hand, opponents of renewable energy point out that base load power plants cannot be shut down within a short time. On the other hand, supporters counter that due to weather and wind forecasts the produced electricity can be accurately predicted one day in advance so that the shutdown of coal and nuclear power plants is viable (Dalheimer 2011). Due to the steam stream, all thermal power plants have a minimum load. They are not able to produce electricity below a certain capacity. Even when the market price decreases below variable costs, base load power plants are still likely to generate. Due to very high start-up costs and opportunity costs, which occur when prices in the following hours rise above variable costs, coal and nuclear power plant operators are not willing to shut off power plants in hours of low prices. The occurrence of negative prices at the European Energy Exchange indicates that shutting down plants in case of low load and high renewable production is not always possible - even if accurate day ahead forecasts are available (Nicolosi 2010). Unusual constellations of demand, supply and weather can lead to periods of negative prices at the European Energy Exchange. In these periods, the energy supplier has to pay for the produced electricity (Nicolosi 2010; Mihm 2009).

Shutting down WPP in periods of very strong winds through the grid operator may seem to be undesirable as it is carbon-free and it causes no variable costs. However, it is practiced in Germany (Die Presse 2013). One of the reasons is, according to the German government, the delayed power grid expansions as well as the lack of storage opportunities (Dalheimer 2011). To address this issue, various technical solutions are available and presented in the subsequent sections. While for most of them, extensive research is being conducted, there is little research on spatial matching of renewable supply and demand available. This issue is therefore addressed in the empirical section of this thesis.

### 2.4.3. Expansion of the Grid

Wind turbines are of course mainly installed in areas with favorable wind conditions, leading to a regionally concentrated expansion of wind power. This can lead to a large production of wind power in regions where the local consumption is low and the surplus needs to be exported. Therefore, a well developed power grid allows integrating higher shares of wind power. The grid must be able to constantly absorb and distribute the produced power (Ibrahim et al. 2011). Therefore, a strong transmission grid is necessary to transport the electricity from windy regions to consumers (Georgilakis 2008). Large-scale interconnected electricity systems are combining large amounts of rapidly changing generation and its loads. This has an averaging effect and therefore allows to better balance demand and supply (Hammons 2008).

But the power grid was built with large centralized generation due to economies of scale. Producers were located close to primary energy resources (coalfields, cooling water, etc.). The power grid system was optimized for regional self sufficiency and interconnections were originally developed for reciprocal support between regions. But the transmission grid is increasingly used for trading between states and enhances overall security of supply (Hammons 2008).

By liberalizing the electricity market, there was a separation of the formally integrated value-added steps within the electricity industry. According to Borgrefe and Nüßler (2009) these steps are production, trade, transmission, distribution, and sales. With the aim to increase efficiency, open competition was introduced to the steps production, trade and sales. But the steps transmission and distribution show the attributes of a natural monopoly. They remain monopolies therefore and are heavily regulated. The liberalization of the electricity market in Austria was promoted through the "Elektrizitätswirtschafts- und Organisationsgesetz (ElWOG). With the Energy Liberalization Act, the third energy liberalization package was implemented into Austrian law, with its emphasis on the seperation of the ownership of transmission power lines from production and distribution ("IG Windkraft" 2013).

At present, there is no internalization of grid externalities caused by single producers, e.g. the increased need for grid expansion due to the choice of locations of power plant investors or the effect of regionally concentrated electricity feed-in on the system safety of the power grid. For a power plant operator, only economical factors considering revenues and costs of power production and sales are crucial for site selection, but grid externalities are not. Especially WPP are linked to specific locations with good wind resources, as they would have to take into account a loss in revenues by using alternative locations with less favorable wind conditions. Effects on the power grid and possible necessary grid expansions are not taken into consideration by wind park developers as they are not bearing those costs (Borggrefe and Nüßler 2009). In Germany, according to the KraftNAV policy (*KraftNAV* 2007) grid operators are obliged to connect new power plants to the grid. Power plant operators have to pay only for the connection between the electricity production site and the power grid.

Another difficulty is that power plant and grid investments have different turnover times. For planning and implementing a new power plant, around 5 years are needed, depending on the size and technology. Planning and implementation of grid expansions take approximately 10 years. So the grid expansion planning is delayed with respect to the power plant development (Borggrefe and Nüßler 2009). So far, power grid limitations are not properly considered in Germany, when it comes to short term power plant uses or long term power plant construction. The suboptimal power plant planning by not taking into consideration the overall energy system, including production, transmission, and consumption, leads to additional costs for the consumers. Therefore, Groschke et al. (2009) suggest that policy instruments should be applied which consider grid limitations when it comes to power plant planning to minimize the costs for the economy as a whole.

Consequences of separated power plant and grid expansion planning are already visible. For instance, in the northern parts of Germany, energy production is more and more concentrated while the highest electricity demand is located in the South and West. One of the reasons for the concentrated electricity production in the North is the good conditions for on- and offshore WPP. The share of produced electricity from wind power and the predicted load at the same hour is an indicator for the rate and extent of electricity exports from North Germany. About 20% of the hours the wind power production exceeds the overall demand, in some hours it is even double as high (Borggrefe and Nüßler 2009). There are still no incentives to site electricity production close to the load in current German policy, because there are no di stance related royalties for power transport. This leads to further challenges for the transmission grid (380 and 220 kV) (Groschke et al. 2009).

In Austria, major investments for the power grid are essential, due to the expansion of power plants from renewable energy sources. According to E-Control (Ometzberger 2012) 220 kilometers of new power lines are planned and a total of 2.5 billion euro are invested into the high voltage network till 2022. The transmission grid investments are not borne by the wind power companies but by the final consumer.

### 2.4.4. Storage

The primary idea of energy storage is to use the electricity from wind power production produced during periods of peak production to supply energy for periods of low wind power penetration or peak demands. Therefore, electricity must be transformed into a storable form of energy like potential, chemical or mechanical and transformed back when needed (Ibrahim et al. 2011). Figure 6 shows the possible smoothing effect of energy storage on the electricity output of WPP.

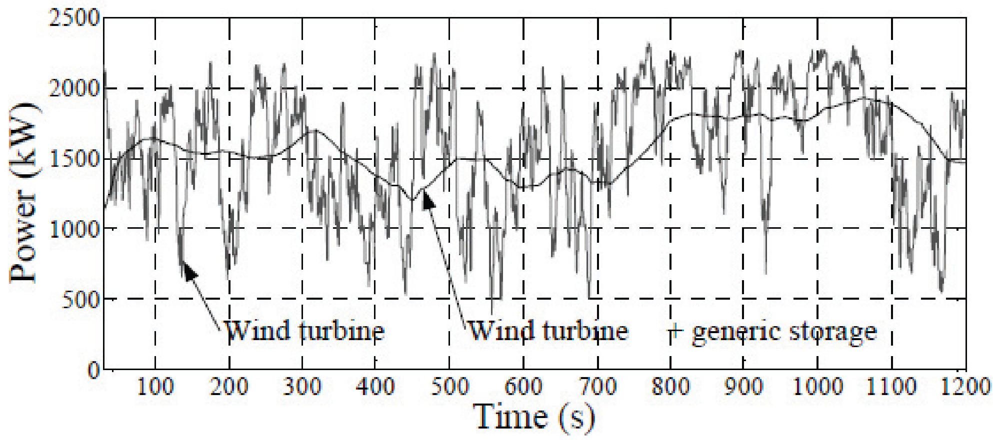



***Figure 6***: *Wind power generation with and without storage; Source: (Ibrahim et al. 2011, 7)*

According to Deru and Torcellini (2007), there has been an increasing demand for the deployment of energy storage as an essential component of future energy systems with a large share of renewables. A main advantage of energy storage is the ability to address several issues with respect to the integration of intermittent electricity production into the power grid such as load leveling, regulating energy, contingency reserves, and firm capacity (Rahman, Rehman, and Abdul-Majeed 2012).

But the 'need' to deploy energy storage in order to enable renewable integration is an economical issue. The amount of storage depends on the costs and benefits of each technology respectively to other available options (Denholm et al. 2010).

The choice which energy storage system is used depends upon the priority such as high energy density, reliability or low cost. The energy storage applications in the electrical power system are often divided into three main categories according to Rahman, Rehman, and Abdul-Majeed (2012):

- Power quality: The required discharge time is only applied for seconds and assures the continuity of quality power. Applications are transient stability and frequency regulations.
- Bridging power: The stored energy in these applications is used for seconds to minutes. It guarantees the continuity of service while switching from one source of electricity generation to another.
- Energy management: The discharge time is hours and a typical application is load leveling. It is applied by storage media, which requires charging when energy cost is low.

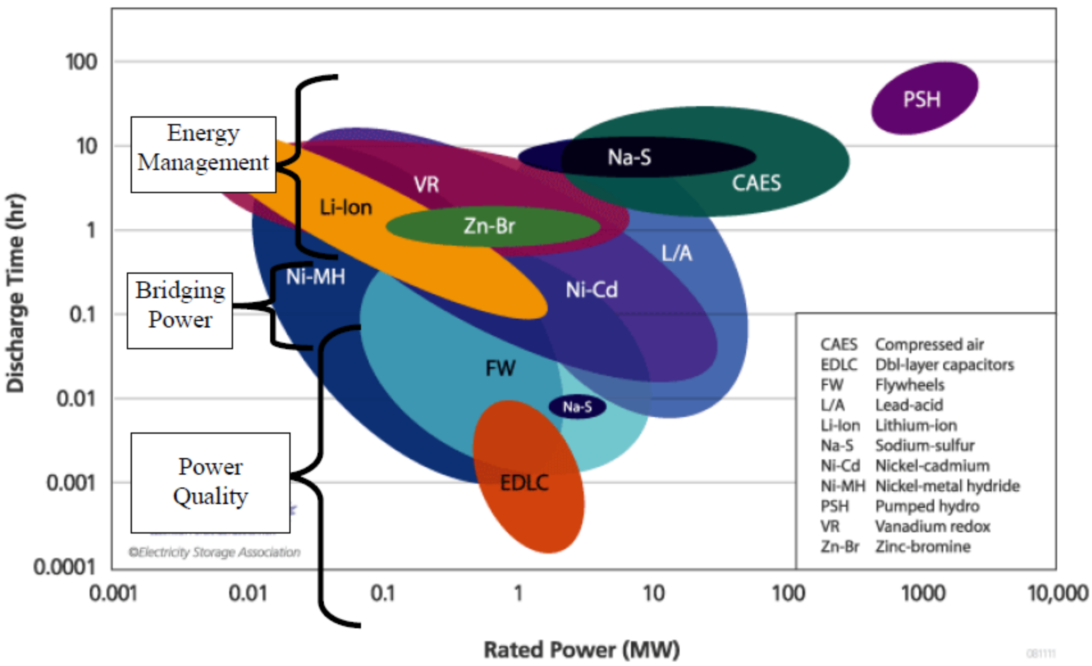



***Figure 7:*** *Energy storage applications and technologies; Source: Denholm et al. (2010, 39)*

Figure 7 provides an ov erview of available technologies for energy storage systems with respect to their discharge time and power output. The worldwide installed electric energy storage capacity is approximately 125 G W, the vast majority comes from pumped hydro (Beaudin et al. 2010). For storing surplus electricity, only a few methods exist (Pickard, Shen, and Hansing 2009). The most common bulk storage technologies are:

- Pumped hydro storage (PHS)

  PHS is used as energy management application for moving power over longer timescales. Pumped hydro facility uses conventional pumps and turbines and consists of two water reservoirs at different elevations which require a significant amount of land and water. By pumping water from the lower to the upper reservoir, power is stored in the form of potential energy of water. For power production, water runs back to the lower reservoir and converts the potential energy through turbines and generators to electrical energy. It represents approximately 3% of the world's total installed power capacity, and 97% of the total storage capacity. Worldwide, more than 250 PHS plants are in commission with an overall installed capacity of 120 GW. In Austria, according to "APG" (2014) a capacity of 3,400 MW is currently installed. PHS has a round-trip efficiency (including losses from pump and generator) from 65 to 85% and discharge capacities of up to 20 hours with a lifetime of over 60 years.

High capital cost ($600-2000/kW), the environmental damage resulting in the flooding of land to make reservoirs and project lead times of typically 10 years limit the application of PHS (Denholm et al. 2010)(Beaudin et al. 2010).

- Compressed air energy storage (CAES)

  CAES is used as an energy management application and is together with PHS the only currently used technology for large scale energy storage. It is based on conventional gas turbine technology and makes use of elastic potential energy of compressed air. Energy is stored by compressing air in an existing underground storage cavern including salt domes or abandoned mines. For power generation, the compressed air is drawn from the storage vessel, heated and expanded though a high-pressure turbine. Afterwards the air is mixed with fuel and combusted in a low pressure gas turbine. A generator is connected to the turbines and produces electricity.
  Currently only two CAES plants are operated worldwide with a capacity of 400 MW. Since electricity and natural gas is used by for CAES, a single point definition of the roundtrip efficiency cannot be easily given, but Beaudin et al. (2010) estimated it with 60 to 80%. The discharge capacity ranges from 2 to 50 hours.

  The need of underground cavern and its reliance on fossil fuels are major disadvantages of CAES. The capital costs of CAES with 400 to 800 $/kW are lower than for PHS as well as the effect on the surface environment, since the storages are underground. CAES systems have failed to work economically by selling the electricity on the spot market and it was proposed to operate solely on the regulating power market for a monthly monetary compensation (Denholm et al. 2010)(Beaudin et al. 2010).

- Lead acid batteries

  Lead acid batteries are used as bridge power and power quality applications including load following and providing contingency reserves. This battery has been used in many different applications for over 130 years and is still commonly used as a small to medium scale electricity storage because of their low cost (300 – 600 $/kW), high reliability and efficiency up to 80%. However, lead acid batteries have low cycle life, low energy density and emit explosive gases and acid fumes (Beaudin et al. 2010; Rahman, Rehman, and Abdul-Majeed 2012).

- Nickel cadmium batteries

  Nickel cadmium batteries are used for similar applications as lead acid batteries but they have a higher energy density and more life cycles. In recent years, sales have declined because of high costs (1000 $/MW) and environmental problems due to the disposal of the toxic heavy metal cadmium (Beaudin et al. 2010; Rahman, Rehman, and Abdul-Majeed 2012).

- Flywheels

  Flywheels are used as power quality applications for frequency regulation and transient stability. They are also used for smoothing wind turbine outputs. Flywheels store power as kinetic energy by causing a disk or rotor to spin on its axis. The amount of stored energy is proportional to the rotors / disks mass. Flywheels have a rapid response, high efficiency (90 – 95%) and very long life cycles. The self discharge rate per day is up to 100% and capital costs are high, they range from $1000 to 5000/kWh (Beaudin et al. 2010; Rahman, Rehman, and Abdul-Majeed 2012).

So far, pumped hydro systems and in some cases lead-acid or nickel cadmium batteries are the only storage systems which are used for short notice support and optimization of electricity generation, transmission and distribution.

### 2.4.5. Spatial diversification

According to Degeilh und Singh (2011), the main challenge in wind energy production lies in the intermittent nature of wind itself. To make wind power more predictable and reduce its variability, wind farms may be spread out across different geographical areas to smoothen out the overall power output. Especially in larger scale systems, it is less likely to experience wind shortages at the exact same time when wind farms are far away from each other (Degeilh and Singh 2011). Small wind farms are more likely to have larger hourly variations in power output than an entire area. In West Denmark for example, it is expected that the energy output of its 2,400 MW capacity varies by 3%, while a wind farm in the same area with a capacity of 5 MW varies by 12% (Beaudin et al. 2010).

In the portfolio approach for an optimal wind power deployment in Europe, Roques, Hiroux, and Saguan (2010) show that wind speed correlations between different wind farms falls as the distance between wind farms widens. The hourly correlation coefficient decrease to approximately 0.1 over distances in excess of 100 km between wind farm sites in the UK. Wind power variations in one part of the country are canceling out variations in wind power in another part of the country and therefore reducing the correlation coefficient (Roques, Hiroux, and Saguan 2010).

### 2.4.6. Matching Supply and Demand

Regionally matching demand and supply by selecting sites accordingly is another solution for the integration problem. The opportunities for renewable integration strategies become apparent by identifying supplies which meet demands. As a result it improves the existing grid by decreasing the load on supra-regional transports (Vitolo et al. 2013; Born 2001).

The following example from Born (2001) demonstrates supply demand matching techniques considering a supply profile from a 3 kW wind turbine system and a small commercial demand profile (figure 8), in a one-week period in June, with U.K. climate.

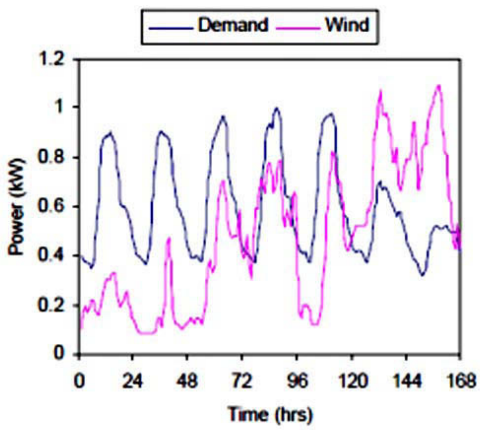



***Figure 8:*** *Matching with wind system; Source: Born (2001, 138)*

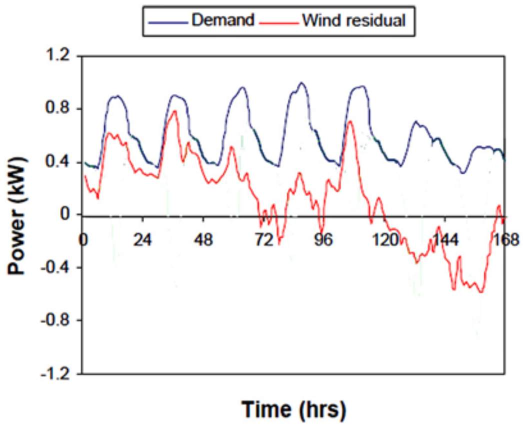



***Figure 9:*** *Comparison of original demand & residual profiles resulting from wind technology deployment, with grid export; Source: Graph created by author, based on Born (2001, 138)*

Two aspects have to be taken into account in matching, magnitude and phase. By only focusing on magnitudes alone, this could lead to waste generation when energy is supplied at times when demand for it is low. Therefore, matching must involve the relative phases of demand and supply. In times when supply exceeds demand the negative residual load must either be exported to the grid or curtailed. Through grid export, the residual variability of load on the grid increases significantly. In large-scale applications this variability could result in grid instability. Curtailing wind power production to a large extent is unfavorable since renewable electricity is wasted and it increases production costs from renewables (Born 2001).

$$r(t) = D(t) - S(t)$$

Described by the equation above the residual, r(t), of two profiles can be obtained by subtracting the supply, S(t), at each time step from the demand, D(t). The residual profile from the previous demand and wind power curve is illustrated in figure 9. The same method is used for calculating the residual load in the scenarios of this work (Born 2001).

Optimizing the residual by specific site selection for wind turbines for spatially matching supply and demand could reduce the stress on the power grid. This issue is addressed in the subsequent empirical section of this thesis.

# 3. Data & Methodology

## 3.1. Overview

Figure 10 provides an overview of the data and methodology for the empirical analysis in the thesis. The detailed description follows below. This thesis investigates to which extent wind power can be ex panded in Austria without major upgrades to the transmission power grid. For that purpose, the electricity flows in the transmission system were optimized by minimizing the residual flows Austria is divided into regions to analyze the local potential wind power production and electricity consumption as well as to calculate the regional residual load which is the difference between regional power load and w ind power production. The division of Austrian is accomplished by using the locations of substations as proxies for electricity demand regions. The household and c ommercial load profiles from Zeyringer and S imoes (2013) are allocated to a s quare kilometer grid and a ggregated within a r egion to a s ingle load curve. The power production of the WWP within a region is also aggregated to a single production curve. Afterwards the residual load and t herefore the surplus power production can be c alculated for every single region. In the scenarios, the minimal residual flow depending on the extent and cost of the expansion can thus be calculated.

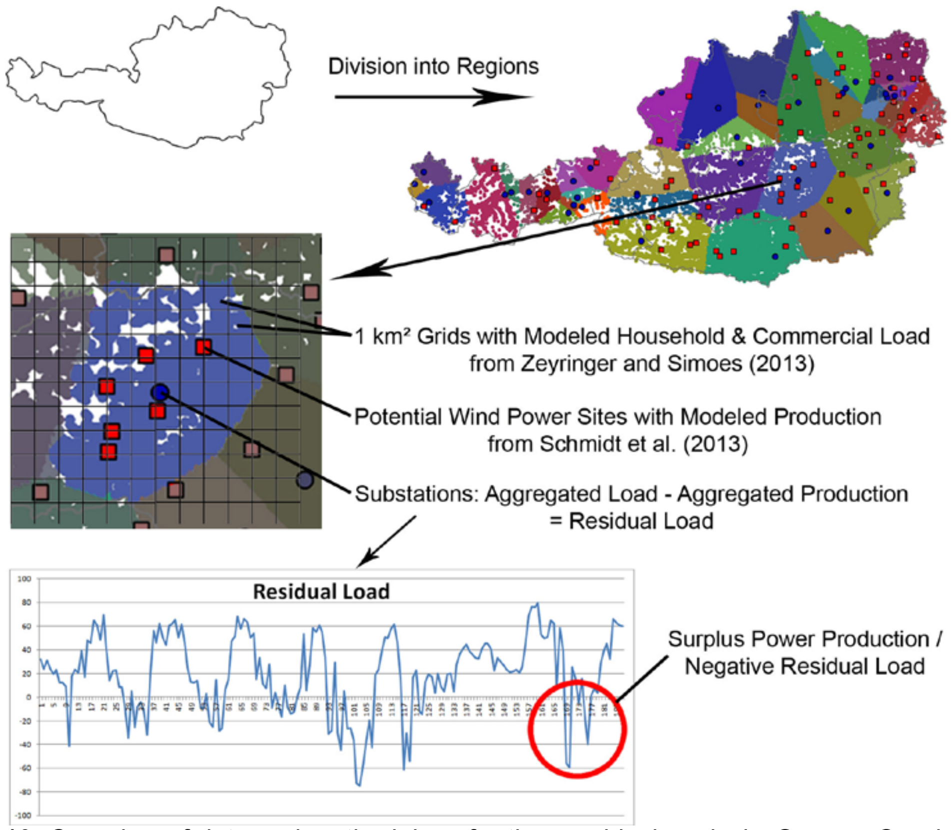



***Figure 10:*** *Overview of data and methodology for the empirical analysis; Source: Graph created by the author*

## 3.2. PRODUCTION DATA

Wind power production data for potential sites were obtained from Schmidt et al. (2013). The wind production data is based on assessment of feasible wind power sites for Austria in Gass et al. (2013). Gass et al. (2013) stated the following technical-legal constrains:

- Elevation: all areas above 2,000m are excluded due to difficulties to access these regions with construction material and to connect it to the power grid.
- Slope: the maximum slope of a site is 15%. All areas exceeding this value are excluded, also because of difficulties to gain access to these regions and the resulting increasing costs for transport, fundament constructions etc.
- Settlement Areas: regional planning legislation differs between the nine federal states in Austria with respect to the definition of minimum distances between WPP and settlement areas. 1,000m is a good compromise involving all different legally set standards for a minimum distance.
- Transport and railroad network: the area of 150m on each side of road and railway traces is also excluded for potential wind power sites.
- Protected Areas: natural conservation areas like Natura 2000 (included in the EU legislative framework on nature conservation, the Birds and Habitats Directive) are excluded.

Graphic 11 shows the methodology of site selection and the detailed modeling steps are described in Gass et al. (2013). In total there were over 5,000 wind turbine locations identified and accumulated to 79 main locations. Sites are considered to be economically feasible, if the levelized costs of electricity at the sites are lower than the guaranteed feed-in tariff of 9.7 c/kWh. Costs and power output are calculated for turbines with an installed capacity of 2 MW. However, 3 MW turbines are already in the approval process (Gass et al. 2013).

The maximum additionally installed wind power capacity at all locations would be 8,452 MW, yielding around 22 TWh of electricity production per year.

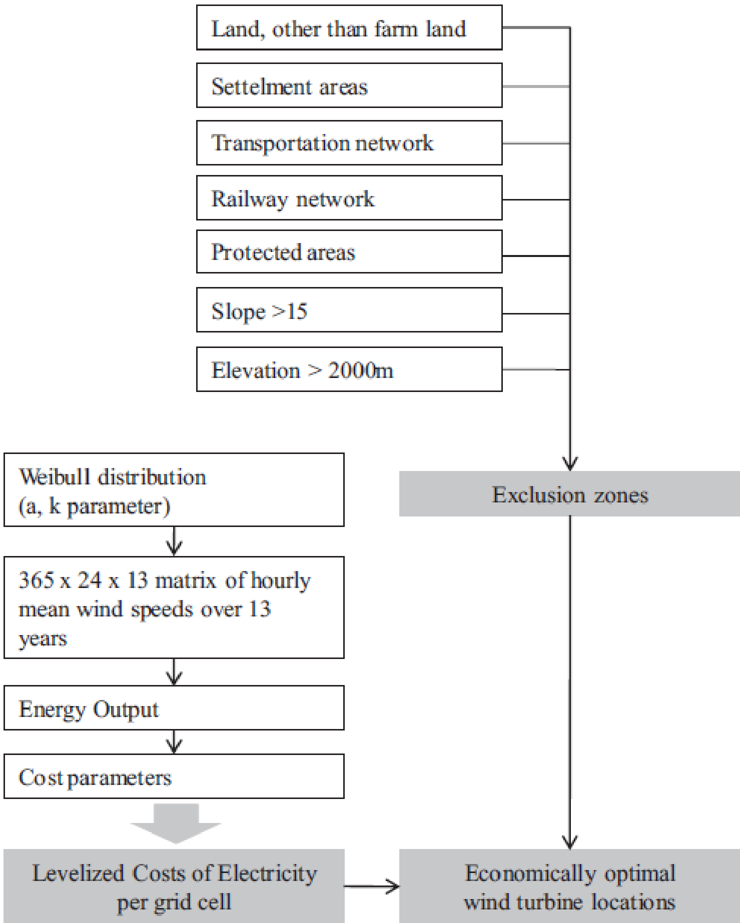



***Figure 11:*** *Overview of the methodology for site selection; Source: Gass et al. (2013, 3)*

In Gass et al. (2013) the levelized costs of electricity were used to identify optimal wind power sites and yields, they did not, however, calculate time series of wind power production. Therefore, the time series of wind speed generated by Schmidt et al. (2013) are used for the analysis. Based on the locations found by Gass et al. (2013), potential wind speed sites were aggregated to 79 subregions. For each of the 79 subregions, a time series was generated, using the Austrian wind atlas, wind data from 265 meteorological stations and technical characteristics of state of the art wind turbines. The methodology is shown in figure 12. With the use of the Austrian wind atlas, scale and shape parameters of existing wind turbines can be derived. Subsequently, wind speeds are randomly drawn from the Weibull distribution and correlated with the closest meteorological station. Historical wind power data was available from 2003 till 2010. To validate the methodology, the historical wind speed time series of the year 2008 is used and compared to the modeled time series. The year 2008 is suitable for the comparison, because locations as well as installed capacities of wind turbines are known and did not change much during this year. For this thesis, the hourly wind speed data from 2009 and 2010 have been used (Schmidt et al. 2013).

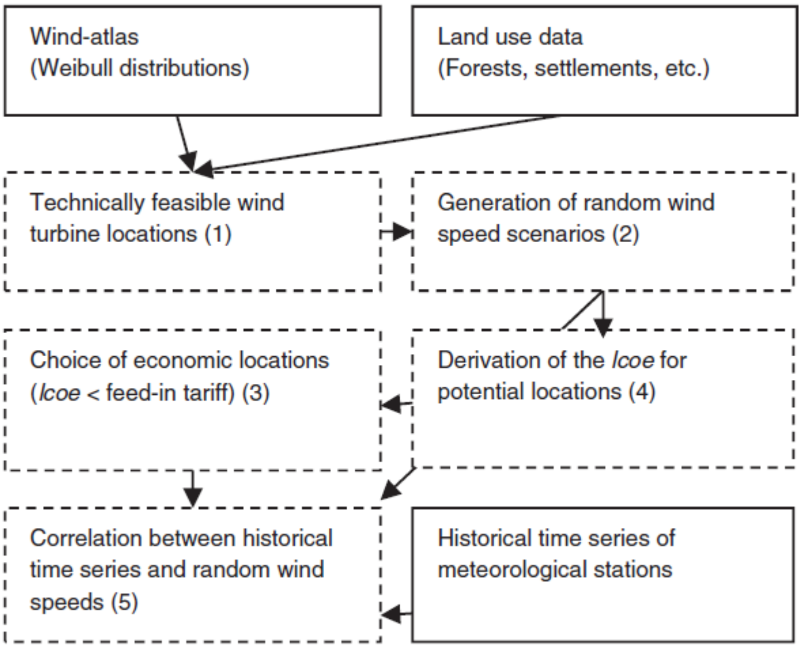



***Figure 12:*** *Methodology to generate synthetic time series of hourly wind production at potential wind power locations. Source: Schmidt et al. (2013, 3)*

## 3.3. LOAD DATA

The load profiles data are taken from Zeyringer and Simoes (2013) which provided data for a period from April 2010 t o April 2011. The estimated load profiles are allocated to a 1km grid for Austria using MGI Austria Lambert R1000 as the Projected Coordinate System. Zeyringer and Simoes (2013) calculated aggregated load profiles for household and small- scale commercial consumers with the help of measured load data to create realistic scenarios. A brief overview of their modeling approach is given here, a detailed description of the methodology can be found in Zeyringer and Simoes (2013). The data source of the load profile differs between the households and the commercial electricity consumption.

### 3.3.1. HOUSEHOLDS

Zeyringer and Simoes (2013) are using 800 measured household load profiles from 33 municipalities in Upper Austria as input for their model. The load profiles were measured with a time resolution of 15 minutes between April 2010 and April 2011. They have been built for three different day types (Weekday, Saturday and Sunday) as well as for three different seasons (summer, interim periods and winter).

There are two approaches to model the load profile for households per grid cell. If the number of households per grid cell is higher than 150, aggregated load profiles are being used as their approximation is sufficiently accurate. If the number is smaller, the load profile is aggregated by picking randomly as many profiles from a pool of measured households according to the number of inhabitants in the cell.

### 3.3.2. COMMERCIAL

For commercial consumers, no measured load profiles are available so the dynamics of variable electricity consumption was created via residuals. This was achieved by excluding all consumers in the grid cell who are not connected to the low voltage distribution grid, like large industrial consumers. Since the number of companies is not given but the number of employees, the number of load profiles simulated in every grid cell was modeled by the average number of employees per enterprise in every section. If the number of employees for grid cells is below the average number, a single load profile is simulated. Otherwise, the standardized load profile which is normalized for a consumption of 1,000kWh is multiplied with the consumption in that grid cell. Standardized load profiles, which are randomized by adding a randomly chosen residual load profile from their set, are picked in each grid cell, scaling it by the number of employees. The commercial load profiles are modulated with a time resolution of 15 minutes between April 2010 and April 2011 (Zeyringer and Simoes 2013).

## 3.4. SUBSTATIONS

The substations are used as proxy for dividing Austria into demand regions. The residual electricity flow is calculated for these regions. Within the regions the production and the demand curves are aggregated to a single load curve. 40 substations were identified in Austria.

Electricity from WPP is mainly fed into the low and medium voltage power grid. Power nodes at this voltage level were not publicly available, therefore substations are used as proxies in this model. Grid cells and wind power sites are allocated to a substation by minimizing distances. Power lines as well as potential obstacles like mountains or rivers are not taken into account.

The locations of the substations were obtained through ENTSOE (2013). However, ENTSOE had not identified or listed all locations of substations in Austria, therefore the available substations were complemented with data from (“Wikipedia” 2013) and orthophotographies from Google Maps.

The respective coordinates of the substations can be found in the appendix.

## 3.5. METHODOLOGY

### 3.5.1. DIVIDING AUSTRIA INTO REGIONS

To examine the local electricity production and consumption, a model is set up which divides the area of Austria into regions. Therefore, the distance to the next substation is used to identify the border of the region, which is schematically depicted as shown in figure 13.

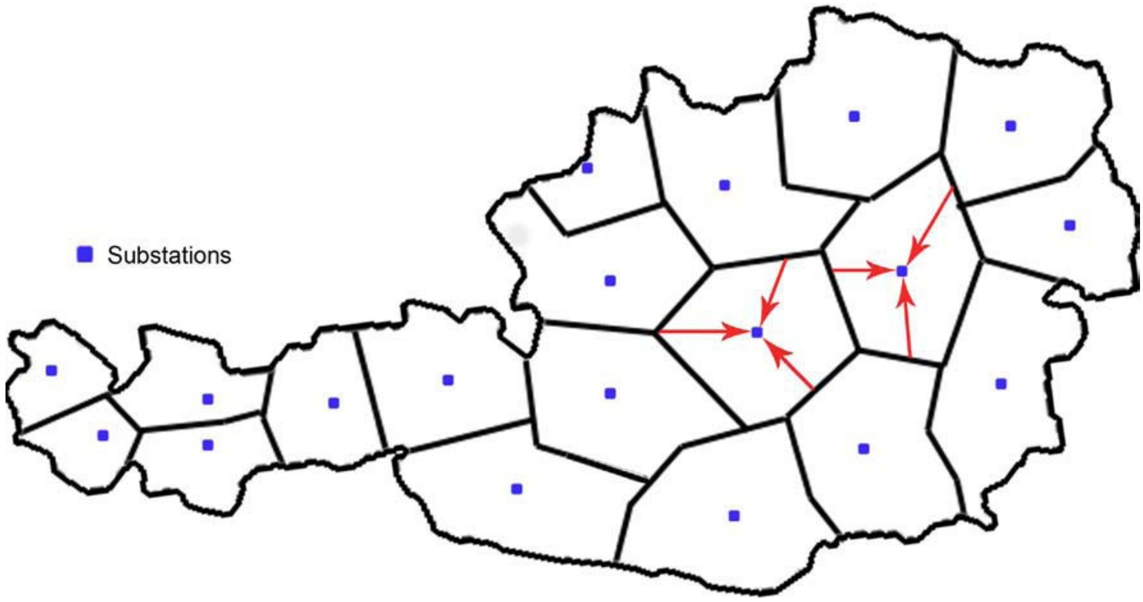



***Figure 13***: *Division of Austria into regions; Source: Graph created by the author*

In order to simplify the research process, obstacles for the power grid like rivers or mountains are not considered in this model. It is assumed that the total residual load within a region is pooled at the allocated substation. An R – program is used to find the nearest substation for every wind power site and household/commercial grid cell. With the help of the geospatial processing program ArcGIS the MGI Austria Lambert R1000 grid can be converted to the World Geodetic System (WGS 84) which operates with longitude and latitude coordinates. Since the coordinates of the substations and the wind power sites are given in this system, this conversion is necessary.

By calculating the distances from every grid point to all substations, the closest one can be identified and allocated. Figure 14 provides an overview of the approach.

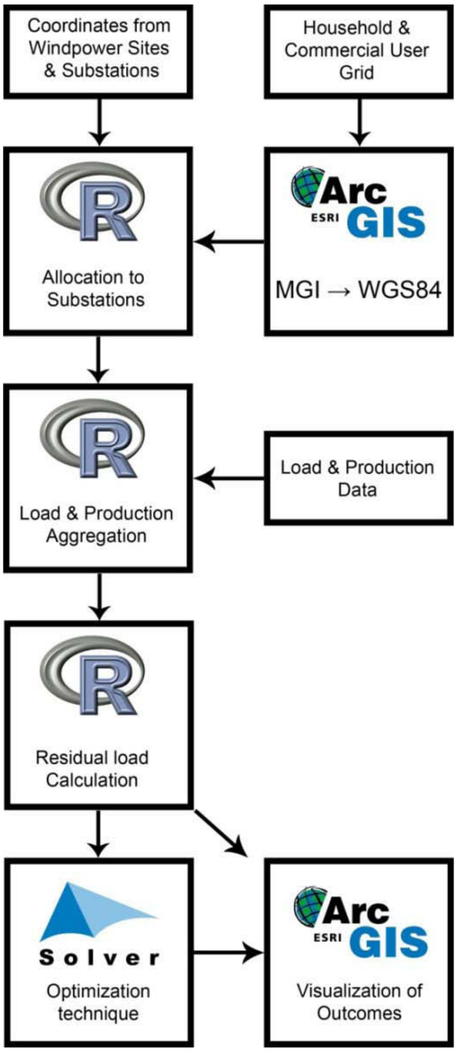



***Figure 14**: Overview of the approach; Source: Graph created by the author*

### 3.5.2. Load and Production Aggregation

Within a region, the hourly production of the potential wind power plants is accumulated at the relevant substations for the whole year to represent an aggregated wind power production for that region. The same procedure is used to accumulate the load of households and c ommercial consumers as illustrated in figure 15. To improve the accuracy of the model, the load data is calibrated with the actual household and commercial consumer data from “E-Control” (2013). Additionally, household and commercial consumption are combined to an aggregated load.

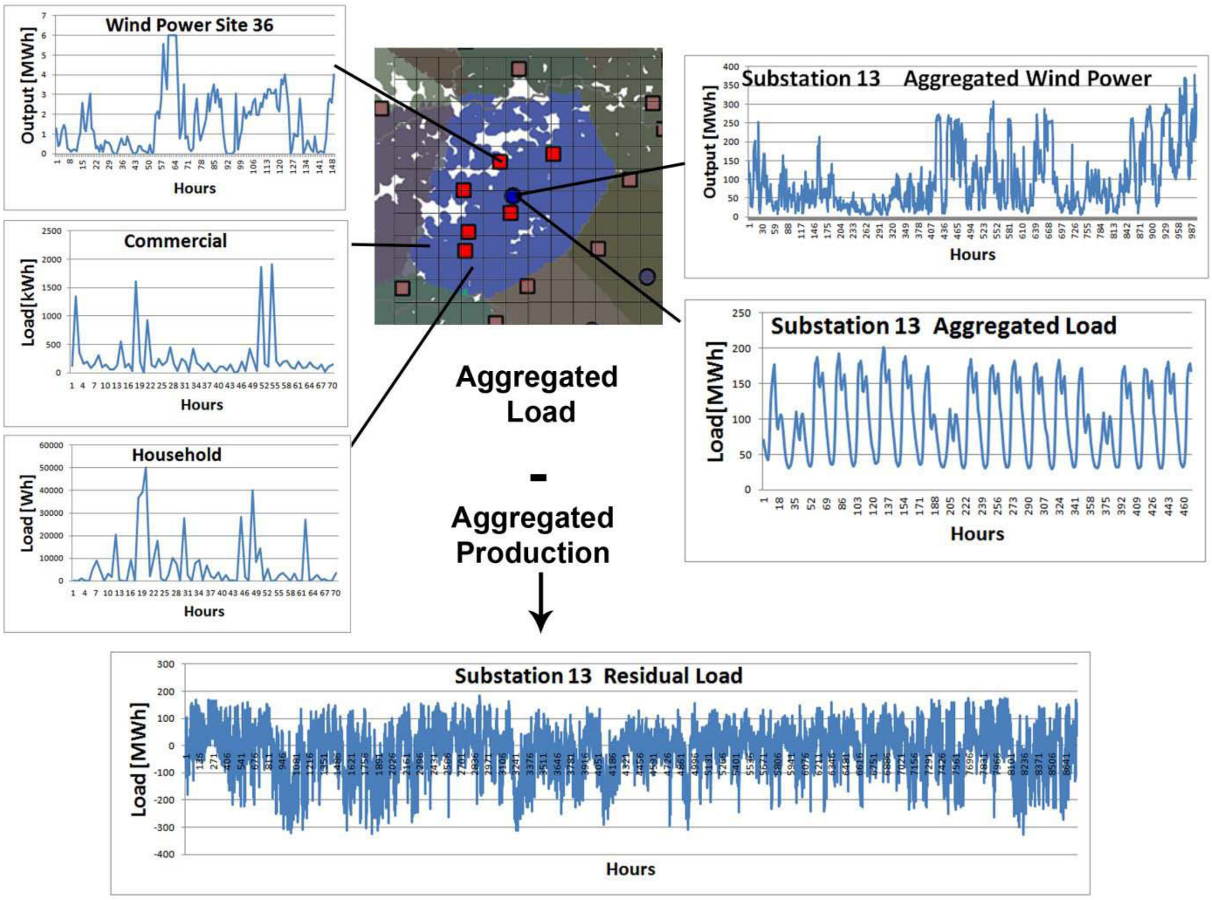



***Figure 15:*** *Schematic description of load and production aggregation; Source: Graph created by the author*

The very large amount of load profile data made it necessary to use databases to facilitate processing of the data. The time resolution of the production is 1 hour, so the resolution of the demand has to be changed from 15 minutes (as in the original input files) to one hour by calculating the mean of 4 measured values in the respective hour. An R-program is used, which reads 1000 lines of consumption data at a time from the database, aggregates them to an hourly time resolution and exports the 250 lines into another database. The program repeats until the whole dataset is converted. A snippet of the R-code is provided below.

```
while(!dbHasCompleted(resCom15min)){
  data15min <- fetch(resCom15min, n = 1000)
  for(i in 1:250)  {
    a<-i*4-3
    b<-i*4
    data1h[i,]<-colMeans(data15min[a:b,])
                    }
  data1h<-as.data.frame(data1h)
  dbWriteTable(con = dbCom, name = " databaseCommercialshours ", value = data1h
,row.names = FALSE, header = FALSE,append=TRUE)
                                                    }
```

For the aggregation, the demand data is loaded fragment by fragment from a database into an R program, where it is aggregated and exported back to a d atabase. The following R-code illustrates the procedure for aggregating the commercial load data. dbConnect() opens the databases. The first database (dbcom) contains the load data with an hourly time resolution for all grid cells with commercial activities (26,903). The second database (dbsum) is used for exporting the aggregated load. The command dbSendQuery() loads the table 'LoadComh' from the database 'dbCom' into the variable 'res'. The while() loop repeats as long as there is still data to fetch from 'LoadComh'. The fetch() function loads only 500 lines out of 8760 at a time as a result of limited internal memory. Running this function again, the next 500 lines are loaded. The array 'ComtoU' contains the numbers of the allocated substations for all 26,903 grid cells and binding it to 'data' is necessary for the subsequent aggregation. The matrix 'sum' has 40 columns, each representing a substation. After executing the two for() loops, it contains the aggregated commercial load for all 500 lines. The first loop is repeated according to the number of commercial grid cells and the second one as often as there are substations. The if() function checks which column of load data has to be allocated to the selected substation and consequently totalized at this substation. After converting 'sum' into a data-frame, the 500 lines are exported to the file 'LoadComSum' into the database 'dbSum'. Every iteration of the while() loop appends 500 lines to this file.

```
dbCom <- dbConnect(SQLite(), dbname="databaseCommercialshours")
dbSum<- dbConnect(SQLite(), dbname="datenbaseSum")
res <- dbSendQuery(dbCom, "SELECT * from LoadComh")
```

```
while(!dbHasCompleted(res))                    {
data<- fetch(res, n = 500)
datahead<-rbind(comtou,data
sum<-matrix(nrow = 500, ncol = 40,data=0)
for(i in 1:lcomkoord)      {
   for(m in 1:lsubstation)          {
     if(datahead [1,i]==m)                 {
       sum[1:500,m]<-sum[1:500,m]+ datahead [2:501,i]
                                  }
                                         }
                                                 }
sum<-as.data.frame(sum)
dbWriteTable(con = dbSum, name = "LoadComSum", value = sum ,row.names = FALSE,
header = FALSE,append=TRUE)
}
```

Before the residual load can be calculated, the commercial and the household load as well as the production data need to be calibrated to improve the accuracy of the model. The E-Control (2013) values for national consumption in 2011 are used for calculating the calibration factor for household and commercial loads. According to E-Control, households consumed 13.2 TWh in 2011. A calibration factor of 1.19 is used as the sum of the consumption in the modeled data is only 11.1 TWh. The model includes only small scale commercial consumers but should account for all commercial and industrial consumption. Therefore, the calibration factor for commercial activities is much higher than the one from the households. The annual consumption from the industrial and t he agricultural sector along with small businesses was 41.1 TWh according to E-Control, yielding a calibration factor of 129.8.

### 3.5.3. Residual Flow Calculation

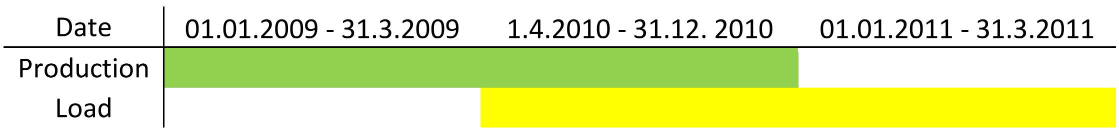
By subtracting the aggregated load from the aggregated production on an hourly basis, the residual load can be i dentified. As already mentioned, the research topic of this thesis is to optimize the residual flow by minimizing the need for electricity flows in the transmission system. A negative residual load indicates that the produced wind power exceeds the local electricity demand at this specific time, causing the need to export it to another region, to store it, or to curtail wind power production.

In the scenarios, which are described in detail later, the following aspects were calculated for every region:

- the percentage of hours where wind power supply exceeds demand,
- the total electricity surplus per year, and
- box plots showing the distribution of the annual residual load.

The R-program is also used for calculating the residual load. Every single hour of aggregated load is subtracted by the same hour of the day from the aggregated wind power production data for every region. Figure 16 shows that the data from electricity production and consumption do not overlap for all 12 months. They overlap from April 2010 to December 2010. No production data are available after the end of December 2010 as well as for the time interval from January 2011 to March 2011, production data from the same months, but from a different year, i.e. 2009, are taken.

***Figure 16:*** *Timetable of electricity production and consumption; Source: Figure created by the author*




### 3.5.4. Optimization Technique and Visualization of Outcome

The optimization program “Solver”, which is premised on “Excel”, has been used to find suitable installed wind power capacities for the different scenarios. The corresponding optimization problems are shown in the subsequent sections. The geo-information program ArcGIS and R -Commander have been used for graphic illustrations and GIS analysis.

## 3.6. SCENARIOS

Four scenarios are analyzed. In a first scenario, the residual flows are assessed using the full wind power potential according to Gass et al. (2013).

Two other scenarios are based on an analysis by Streicher et al. (2010). They assess how much wind power is necessary in Austria to become energy self-sufficient by 2050. My scenarios indicate which of the potential wind power sites should be built and to which extent they reach this target. In particular, the construction costs and the supra-regional power flows are assessed using the negative residual load in the regions. Streicher et al. (2010) calculated a share of wind power of 13.9 TWh for attaining self-sufficiency in Austria. Wind power produced approximately 2.4 TWh electricity in 2012. Therefore, an additional production of 11.5 TWh is needed and assumed in the scenarios.

A further scenario takes into account, how a constraint on supra-regional power flows would affect the total annual wind power potential in Austria.

***Table 2:*** *Cost and numbers of turbines per region; Source: Table created by the author based on data from Schmidt et al.(2013)*

| Region Number | Max. Number of Turbines / Region | Average Cost / Turbine [€] | Region Number | Max. Number of Turbines / Region | Average Cost / Turbine [€] |
|---|---|---|---|---|---|
| **R3** | 1245 | 3.491.895 | **R33** | 13 | 3.585.860 |
| **R4** | 79 | 3.514.290 | **R35** | 38 | 3.573.931 |
| **R6** | 3 | 3.534.604 | **R41** | 9 | 3.602.393 |
| **R8** | 6 | 3.624.902 | **R42** | 2 | 3.700.047 |
| **R9** | 60 | 3.575.659 | **R43** | 68 | 3.620.471 |
| **R13** | 191 | 3.624.188 | **R44** | 75 | 3.519.446 |
| **R14** | 1180 | 3.555.843 | **R45** | 1 | 3.487.601 |
| **R15** | 241 | 3.623.519 | **R46** | 3 | 3.651.254 |
| **R16** | 2 | 3.508.314 | **R47** | 9 | 3.628.386 |
| **R23** | 7 | 3.636.501 | **R48** | 122 | 3.483.484 |
| **R24** | 258 | 3.531.747 | **R50** | 237 | 3.492.310 |
| **R26** | 75 | 3.587.416 | **R51** | 127 | 3.501.056 |
| **R27** | 5 | 3.507.569 | **R53** | 63 | 3.477.033 |
| **R29** | 36 | 3.505.368 | **R54** | 9 | 3.652.903 |
| **R30** | 62 | 3.508.058 | | | |

For all scenarios, the maximum of installed wind turbines per region are given and the cost per wind turbine and site is shown in table 2. Not every region has potential wind power sites and therefore not all regions are listed in the table above. The respective location of the regions is shown in Chapter 4, figure 16 & 17. If a region has more than one wind power site, the average cost of all wind power sites in this region is calculated. The type of the turbine is assumed to be the same in all scenarios.

### 3.6.1. Scenario Maximum Wind Power Expansion

In this scenario, the supra-regional power flow is calculated in case of maximum deployment of all 79 wind power sites.

$$obj: \sum_{i=1}^{54} P_i \rightarrow max$$

$P_i$… Power Produced in Region i (MWh)

### 3.6.2. Scenario Wind Costs Minimized

This scenario does not consider at all supra-regional power flows, it simply minimizes the investment costs for wind turbines. An optimization model looks for the cheapest combination of wind turbines to produce 11.5 TWh, i.e. the necessary amount of electricity to reach the energy self-sufficiency target. The model has the following three equations:

$$obj: \sum_{i=1}^{54} X_i CC_i \rightarrow min$$

$$s.t.$$

$$\sum_{i=1}^{54} X_i P_i = 11.5\ TWh$$

$$0 \leq X_i \leq 1, \forall i$$

$CC_i$… Total Construction Costs in Region i (€)

$P_i$… Power Produced in Region i (MWh)

$X_i$… Decision variable (share of potential built in the region)

### 3.6.3. Scenario Power Flows Minimized

This scenario focuses on minimizing the supra-regional power flows, suggesting that 11.5 TWh of wind power are produced by the potential WPP. With an optimization model the smallest supra-regional power flow for the required electricity production is calculated. The model has the following three equations:

$$obj: \sum_{i=1}^{54} X_i NR_i \rightarrow min$$

$$s.t.$$

$$\sum_{i=1}^{54} X_i P_i = 11.5\ TWh$$

$$0 \leq X_i \leq 1, \forall i$$

$NR_i$… Negative Residual Load in Region i (MWh)

$P_i$… Power Production in Region i (MWh)

$X_i$… Decision variable (share of potential built in the region)

### 3.6.4. Scenario Limited Power Flows

This scenario does not focus on achieving energy self-sufficiency as the previous ones. It deals with the question of how much wind power could be additionally produced in Austria while keeping the supra-regional power flows at a certain minimum. In this scenario, the annual power production is limited to a certain share of negative residual load per region. For the calculation in the optimization model, the share starts from no supra-regional power flow at all (0%) and is continuously increased up to the share of 55%. At the same time the electricity production should be as large as possible. The optimization models' attributes are following:

$$obj: \sum_{i=1}^{54} \mathrm{X_i} P_i \rightarrow max$$

$$s.t.$$

$$\mathrm{X_i} NR_i \Big/ (R_i + NR_i) \leq tar\%$$

$$0 \leq X_i \leq 1, \forall i$$

$NR_i$… Negative Residual Load in Region i (MWh)

$R_i$… Residual Load in Region i (MWh)

$P_i$… Power Production in Region i (MWh)

$X_i$… Decision variable (share of potential built in the region)

$tar\%$…maximum target share of negative Residual Load to total Residual Load

# 4. RESULTS

## 4.1. REGIONAL DIVISION

The whole area of Austria is divided into 40 regions while the closest distance to the next substation is crucial for the border of the region. Potential wind power sites are located in 29 regions; the other 11 do not have any wind power production and are not relevant for this thesis therefore. In figure 17, the regions and their corresponding identification number can be identified.

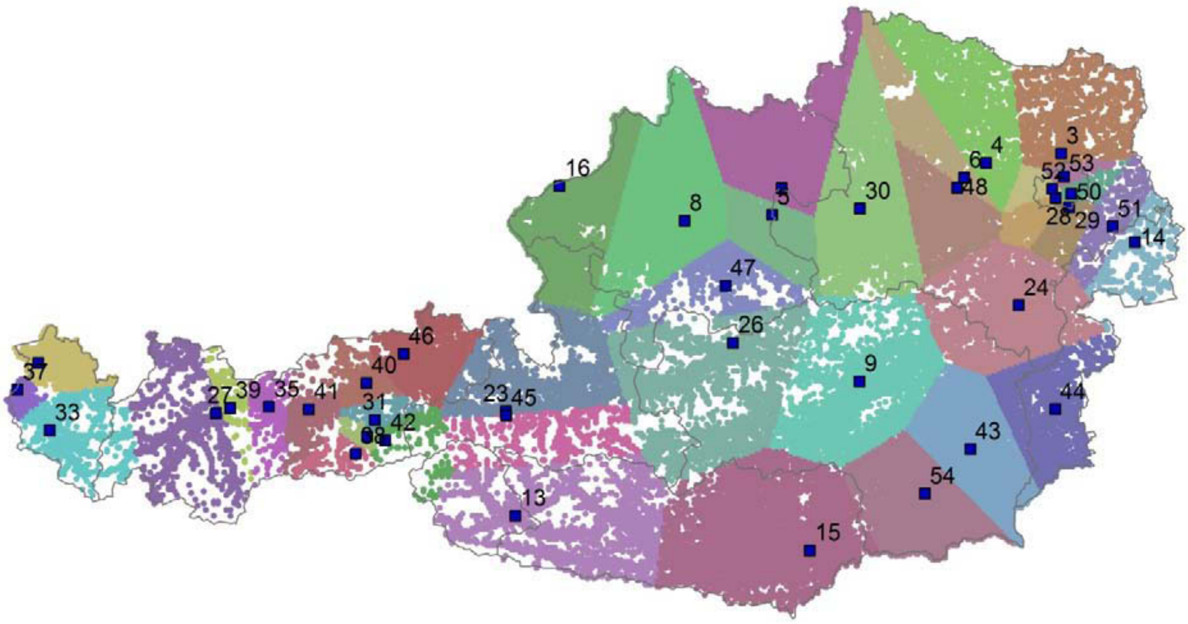



***Figure 17**: Austria separated into regions; Source: Graph created by the author*

Due to the amount of substations and therefore higher number of regions around Vienna, figure 18 gives a more detailed insight for this part of Austria.

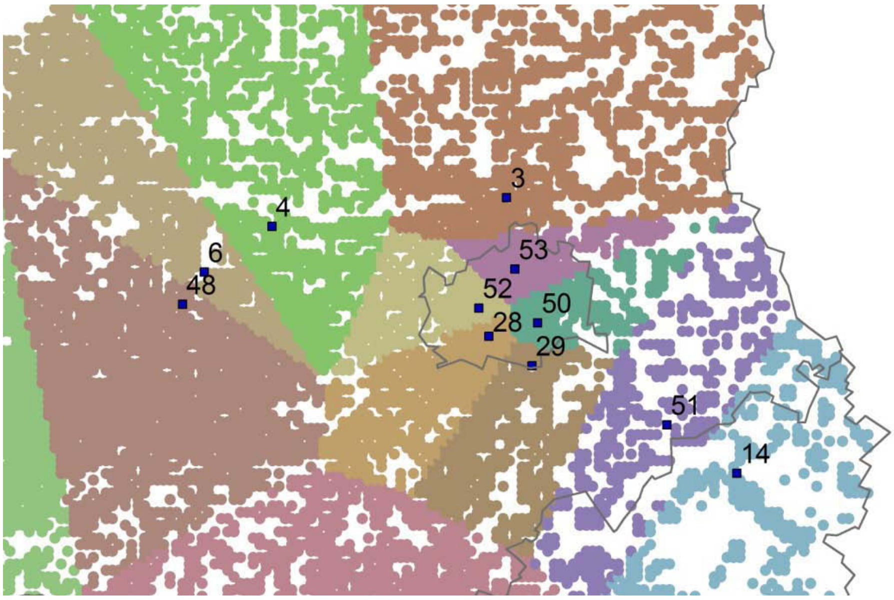



***Figure 18***: *Regions around Vienna; Source: Graph created by the author*

## 4.2. SCENARIO MAXIMUM WIND POWER EXPANSION

Figure 19 shows the share of negative regional residual load to the total regional residual load if all 79 wind power sites are fully installed. This would cause an annual electricity production of 22.4 TWh, a total supra-regional power flow of 13.5 TWh and overall costs of 14.9 billion euro for the installation of the wind turbines, not taking into account the necessary grid extensions.

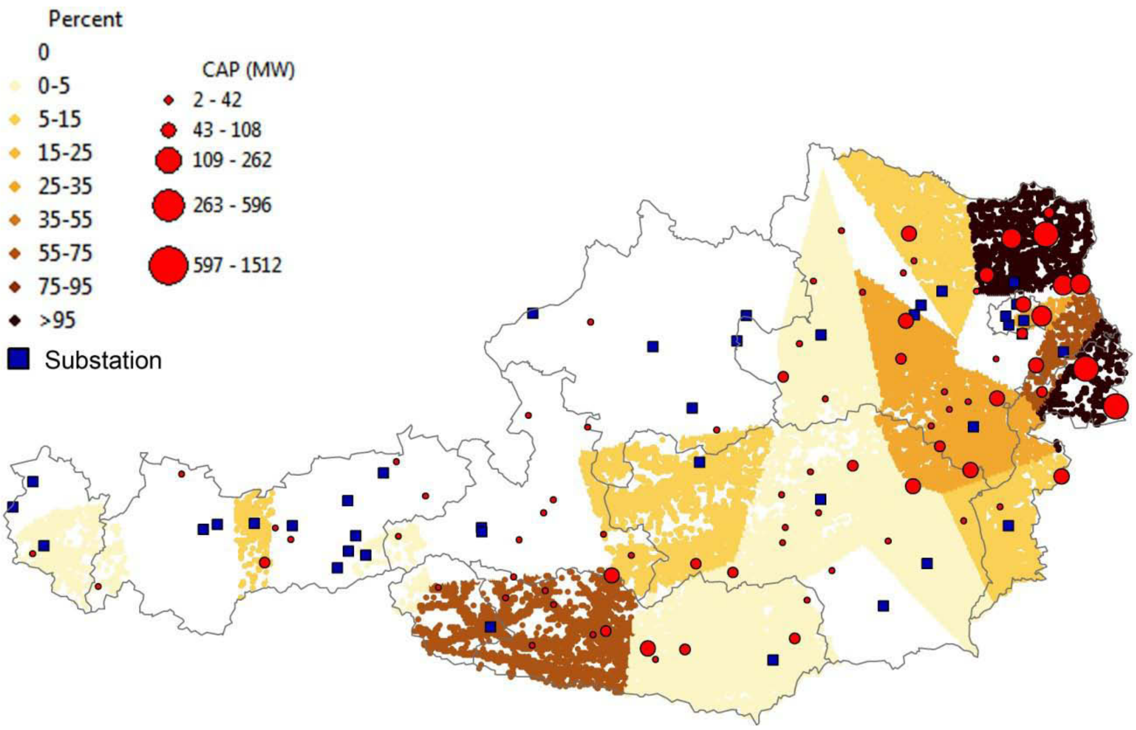



***Figure 19:*** *Share of negative residual load to total regional residual load, at maximum wind power expansion; Source: Graph created by the author*

The size of the red circles indicates the capacity of the wind power sites and the blue squares tag the substations. Hotspots for major new installed power plants are the Weinviertel (Region 3) and the northern parts of Burgenland (Region 14). These regions also produce a major surplus in the local electricity production leading to a share of supra-regional power flow larger than 99%. The western parts of Carinthia (Region 13) as well as eastern parts of Lower Austria (Region 51) also show a high surplus power production with a negative residual load share between 60% and 65%. Regions around Vienna have a medium surplus power production with a negative residual load share of maximal 33%. Besides the two regions 26 and 35, the rest of Austria's surplus production is minor with a negative residual load share of lower than 5%, including Vorarlberg, Tirol, Upper Austria and parts of Salzburg and Styria. This indicates that in these regions there are no wind power sites or the potential wind power sites can be constructed to their full extent without producing large quantities of electricity which needs to flow into the transmission system.

***Table 3:*** *Share of electricity surplus (negative residual load share) and annual production; Source: Table created by the author*

| Region Number | Share of Surplus [%] | Electricity Production/ Year [MWh] | Region Number | Share of Surplus [%] | Electricity Production/ Year [MWh] |
|---|---|---|---|---|---|
| **R3** | 99,91 | 6.840.682 | **R33** | 0,32 | 75.735 |
| **R4** | 6,21 | 404.800 | **R35** | 13,68 | 187.405 |
| **R6** | 0,00 | 16.526 | **R41** | 0,00 | 50.506 |
| **R8** | 0,00 | 37.818 | **R42** | 1,62 | 8.988 |
| **R9** | 0,10 | 332.660 | **R43** | 3,96 | 377.239 |
| **R13** | 61,50 | 1.005.793 | **R44** | 11,25 | 375.635 |
| **R14** | 99,68 | 6.047.473 | **R45** | 0,00 | 5.324 |
| **R15** | 1,47 | 1.029.907 | **R46** | 0,00 | 14.843 |
| **R16** | 0,00 | 9.301 | **R47** | 0,00 | 61.538 |
| **R23** | 0,00 | 36.372 | **R48** | 32,92 | 676.393 |
| **R24** | 31,86 | 1.416.283 | **R50** | 32,30 | 1.351.077 |
| **R26** | 10,33 | 436.793 | **R51** | 66,69 | 645.506 |
| **R27** | 0,07 | 223.747 | **R53** | 0,05 | 338.689 |
| **R29** | 0,75 | 338.223 | **R54** | 0,00 | 43.746 |
| **R30** | 0,32 | 75.735 | | | |

In table 3, the residual load shares and the regional electricity production are shown. A total of 3 TWh per year can be produced in these regions without expanding into regions with a higher share of surplus production.

## 4.3. Scenario Wind Costs Minimized

To achieve an annual electricity production of 11.5 TWh in this scenario, 2,071 turbines with a total capacity of 4,142 MW are installed. The installation cost for these turbines is approximately 7,253 million euro.

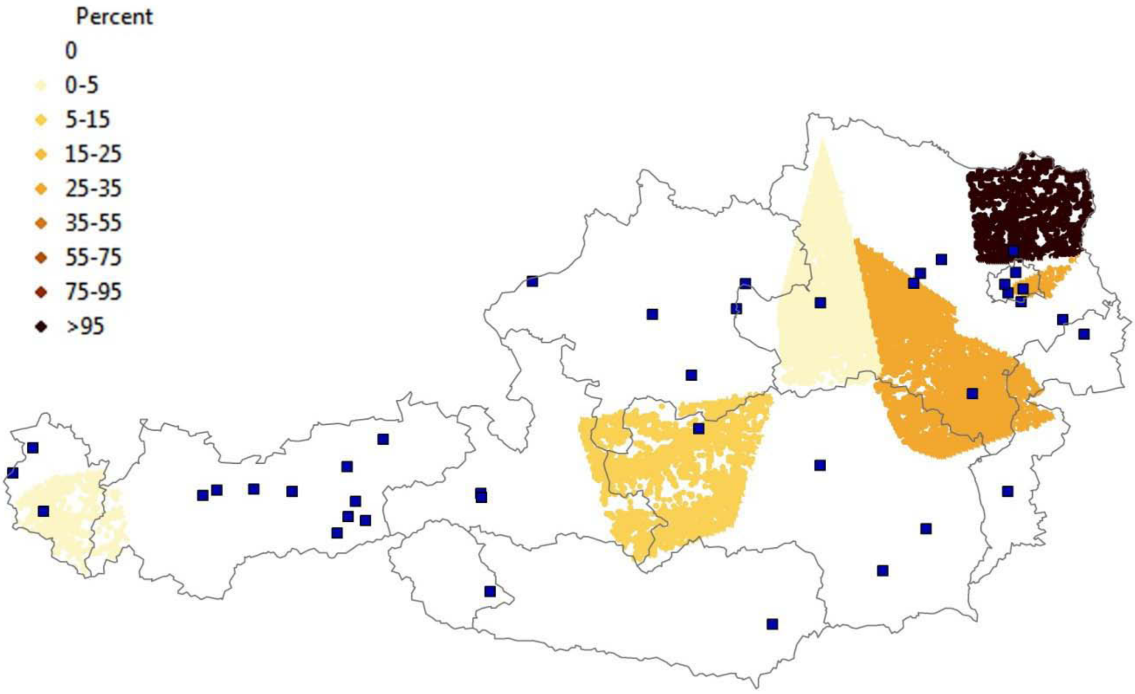



***Figure 20****: Share of negative residual load to total regional residual load, in Wind Costs Minimized Scenario; Source: Graph created by the author*

Figure 20 shows the share of negative regional residual load for the Wind Cost Minimized scenario. The regional energy production and the supra-regional energy flows, clearly indicate that the installed capacities are unequally distributed and centered especially in the Weinviertel area (Region 3). This area has already one of the highest densities of installed WPP in Austria as shown by Figure 2 in Chapter 2. Due to favorable geographic conditions and high average wind speeds the whole potential in this region (1245 wind turbines) would be exhausted. This would lead to a residual flow share of over 99% additionally to the already existing installed capacities. There are also residual flows in the southern parts of Lower Austria (Region 24 & 48) with a share of about 32% compared to the total flow. The electrical surplus in Region 3 is 5,961 GWh and the residual flow from all regions combined is 6,957 GWh. Around 60% of the produced electricity cannot be consumed within the region and needs to be exported.

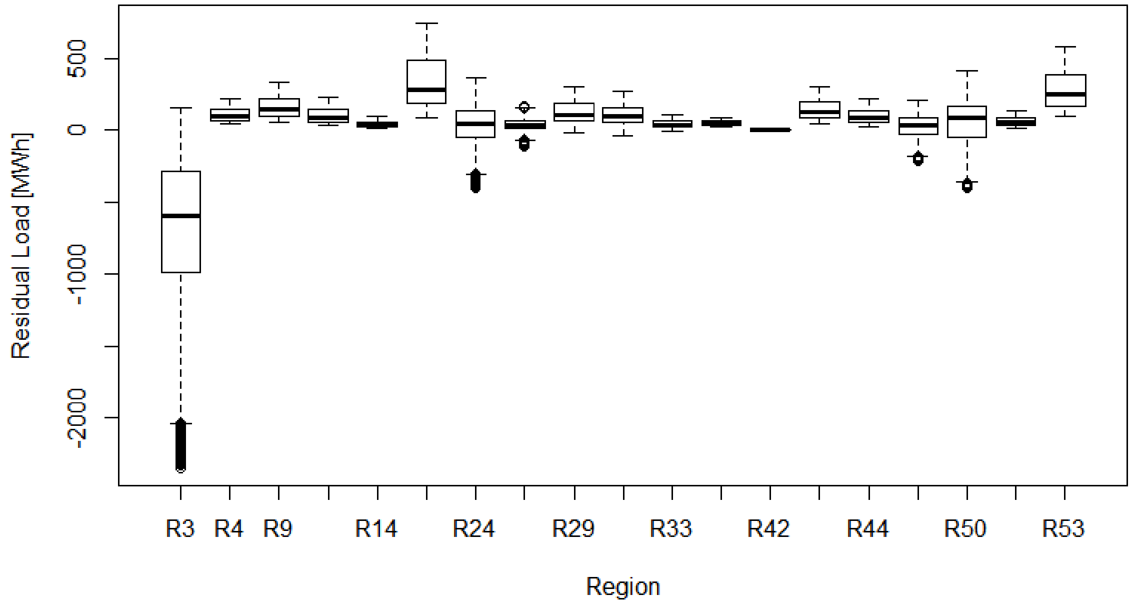



***Figure 21****: Boxplot: Residual load in Wind Costs Minimized Scenario; Source: Graph created by the author*

The boxplot in figure 21 shows the regions where negative residual loads would occur. Due to the large installed capacity in Region 3 only the upper whisker reaches a positive value. For all other regions the median is positive. For Regions 24, 48 and 50 the lower quartile is below zero.

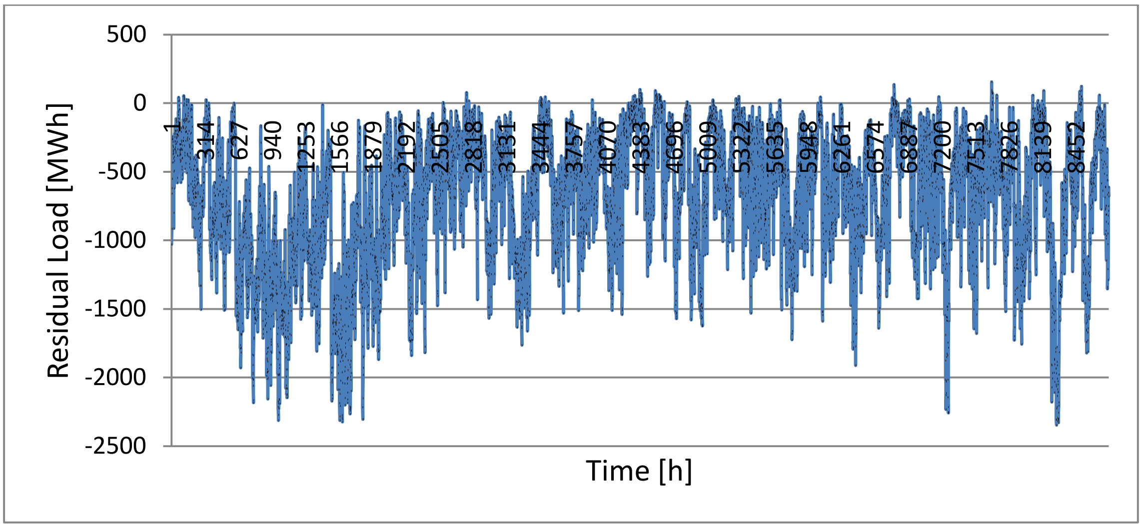



***Figure 22****: Residual load in Region 3; Source: Graph created by the author*

Figure 22 shows the hourly load profile of region 3 over the whole year and depicts the large amounts of produced electricity which is not consumed within the region.

## 4.4. SCENARIO POWER FLOWS MINIMIZED

For this scenario, an annual electricity production of 11.5 TWh is achieved by installing 2,167 wind turbines with a power output of 4,334 MW. The installation costs for these turbines are 7,667 million euro. In comparison to the Wind Costs Minimized Scenario, the costs are 5.7% higher. The higher costs result from having to expand at different wind power locations with slightly lower productivity, resulting in a higher number of installed wind turbines. Since this scenario tries to minimize surplus production within regions to avoid electricity transportation, not all locations with the best energy output could be used. Therefore, 96 more turbines would have to be installed in this scenario to allow the same electricity production as in the Wind Costs Minimized scenario.

The surplus production can be seen in figure 23. Also in this scenario, region 3 has the highest share of negative residual load of 85.1% but in total values it is much smaller (694 MWh). The surplus production is more equally distributed over Austria. Parts of the large potential in Burgenland are used - and also Carinthia has an electricity surplus. The annual aggregated surplus production from all regions is 2,865 GWh and therefore over 58% lower than in the Wind Costs Minimized scenario. 25% of the produced electricity needs to be supra-regionally exported.

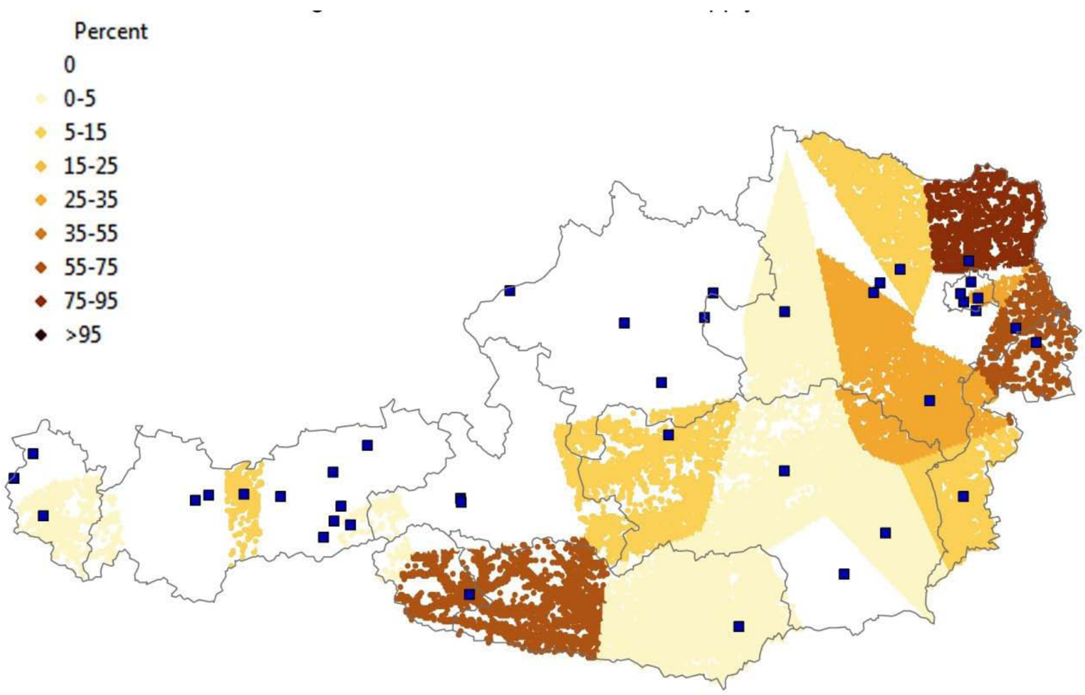



***Figure 23:*** *Share of negative residual load to total regional residual load, in Power Flows Minimized Scenario; Source: Graph created by the author*

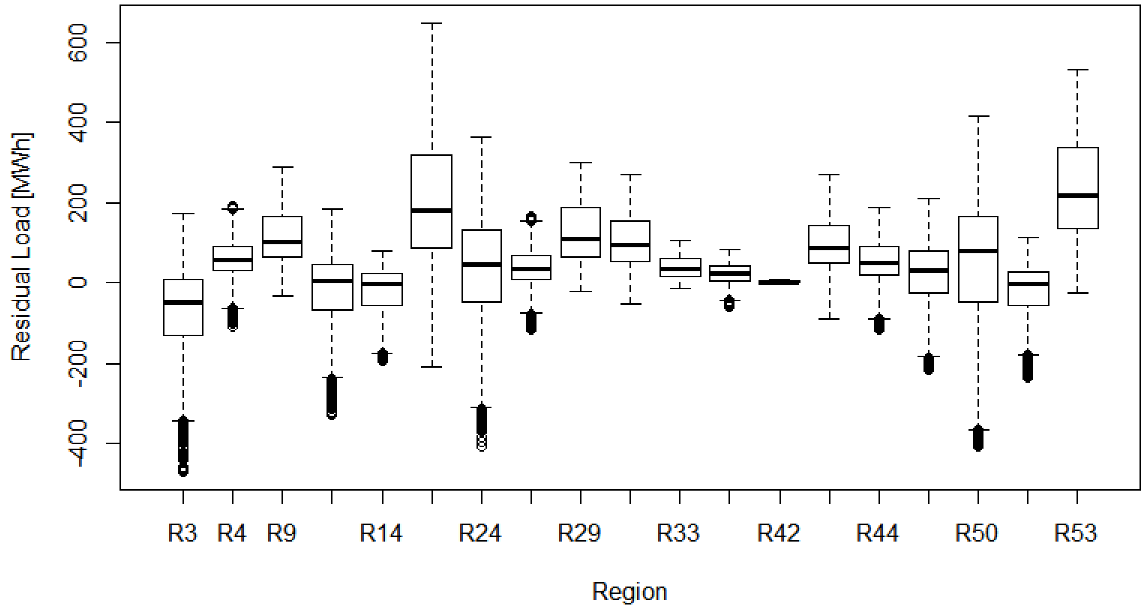



***Figure 24**: Boxplot of Residual Load in Power Flows Minimized Scenario; Source: Graph created by the author*

A significant difference of the Economic and the Power Flows Minimized scenario can be seen by comparing the boxplots in figure 24. While in region 3 residual flows of over 2,000 MW occur in the former scenario, in the later scenario the negative load flows are limited to 450 MW. The lower quartiles of 8 boxplots have a negative value and 3 medians are below zero.

***Table 4:** Comparison of Wind Cost Minimized and Power Flows Minimized Scenario; Source: Table created by the author*

| Scenario | Costs | Installed Capacities | Sum of Negative Residual Load | Maximum Negative Residual Load |
|---|---|---|---|---|
| **Wind Costs Minimized** | € 7.251M | 4142 MW | 6957 GWh | 2346 MW (Region 3) |
| **Power Flows Minimized** | € 7.677M | 4334 MW | 2865 GWh | 468 MW (Region 3) |

In table 4, a summary of the results from the scenarios Wind Cost Minimized and Power Flows Minimized is shown. The boxplots in figure 25 consists of the hourly electricity production combining all regions. The outcome of both annual electricity productions is 1312 MWh per day. The 95 percent confidence interval in the Wind Costs Minimized scenario is [1299.35; 1326.28] and the standard deviation is 641.36. In the Power Flows Minimized scenario the 95 percent confidence interval is [1301.29; 1324.28] and the standard deviation is 548.77.

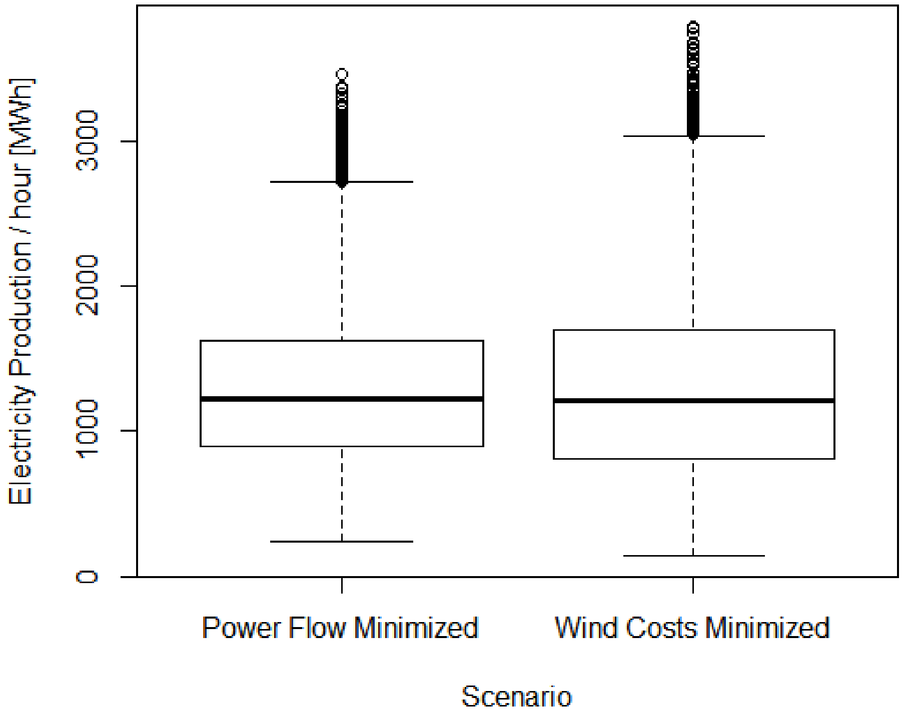



***Figure 25:*** *Boxplot of regionally aggregated electricity production from Power Flows Minimized and Wind Costs Minimized scenario; Source: Graph created by the author*

## 4.5. SCENARIO LIMITED POWER FLOW

The previous scenarios are forcing a fixed amount of electricity output of wind turbines. This scenario focuses on the share of residual load. The aim is to calculate the highest annual energy production with a restricted share of negative residual load per region. The first calculation is made with a share of zero, this means during the whole year, in all of the 29 energy producing regions, no energy surplus occurs at all.

The Figure 26 shows how the total annual wind power production relates to the maximum allowed share of negative residual load per region. The shape of the curve resembles the form of a saturation curve with a very steep incline of annual electricity production during the first few increases in residual share. But at shares higher than 10% the annual production slowly flattens out.

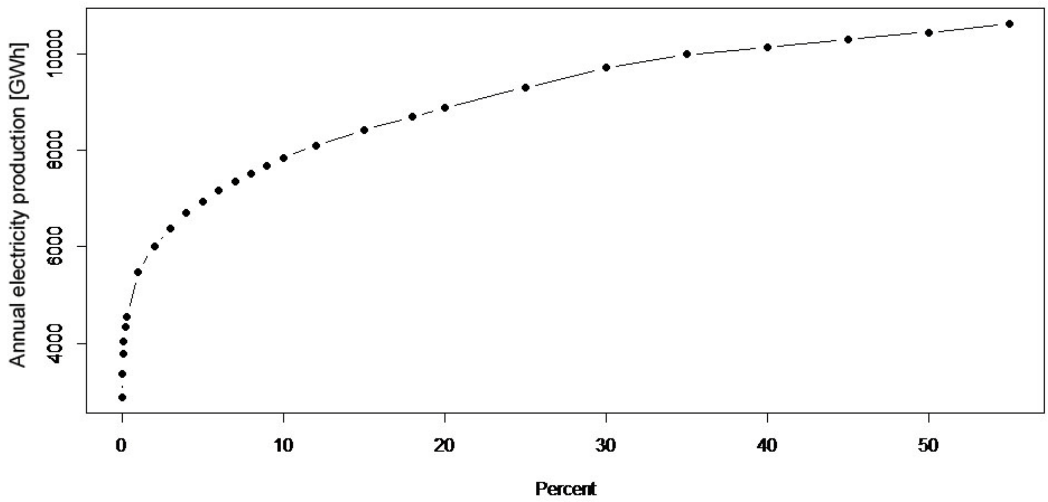



***Figure 26**: Annual electricity production depending on maximal negative residual share per region; Source: Graph created by the author*

By not allowing any residual flow at all, the installed capacity is restricted to 1,086 MW producing 2.8 TWh annually with installations costs of 1.93 billion euro. By increasing the restriction of the residual share to 0.5% per region, the installed capacity rises to 1,442 MW with an annually production of 3.8 TWh as can be observed in table 5 and furthermore, the installed capacity almost doubles if a share of 1% is allowed. A different trend can be seen in Figure 27 which shows the supra-regional electricity flow depending on t he residual share. This curve is almost linear through the whole observed parameter space. Doubling the residual share percentage increases the supra-regional electricity flow of approximately 70% with deviations at the lowest and highest end on the X-axis.

***Table 5**: Limited Residual Load; Source: Table created by the author*

| Residual Share [%] | Supra-regional Electricity Flow [GWh] | Annual Electricity production [GWh] | Overall Costs [mil €] | Installed Capacity [MW] |
|---|---|---|---|---|
| 0,00 | 0,059 | 2.881 | 1.930 | 1086 |
| 0,01 | 1,592 | 3.360 | 2.264 | 1274 |
| 0,05 | 7,702 | 3.795 | 2.563 | 1442 |
| 0,10 | 14,415 | 4.054 | 2.741 | 1542 |
| 0,20 | 26,081 | 4.353 | 2.951 | 1660 |
| 0,30 | 37,042 | 4.559 | 3.094 | 1740 |
| 1,00 | 119,365 | 5.486 | 3.738 | 2102 |
| 2,00 | 194,440 | 6.005 | 4.089 | 2300 |
| 3,00 | 267,825 | 6.384 | 4.337 | 2440 |
| 4,00 | 339,391 | 6.699 | 4.542 | 2556 |
| 5,00 | 400,561 | 6.941 | 4.701 | 2646 |

The boxplots in Figure 28 shows the distribution of the energy production in the 29 regions which have WPP. The residual share is limited to one percent per region. All lower quartiles are positive. The minimum indicator reaches a negative value except in regions where the potential wind power is not sufficient enough to produce a surplus. In this scenario, these regions are exploited to their full extent. In total, the installed capacity is 2,102 MW with an annual production of 5.48 TWh and a supra-regional residual load of 119 GWh.

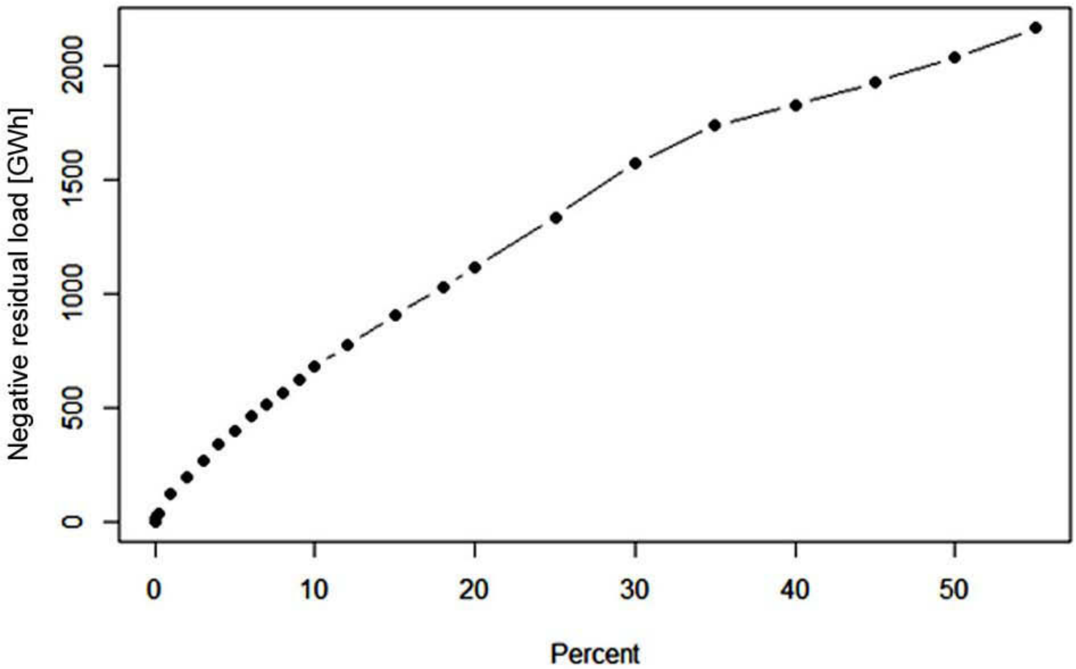



***Figure 27***: *Total supra-regional electricity flow depending on maximum negative residual share per region; Source: Graph created by the author*

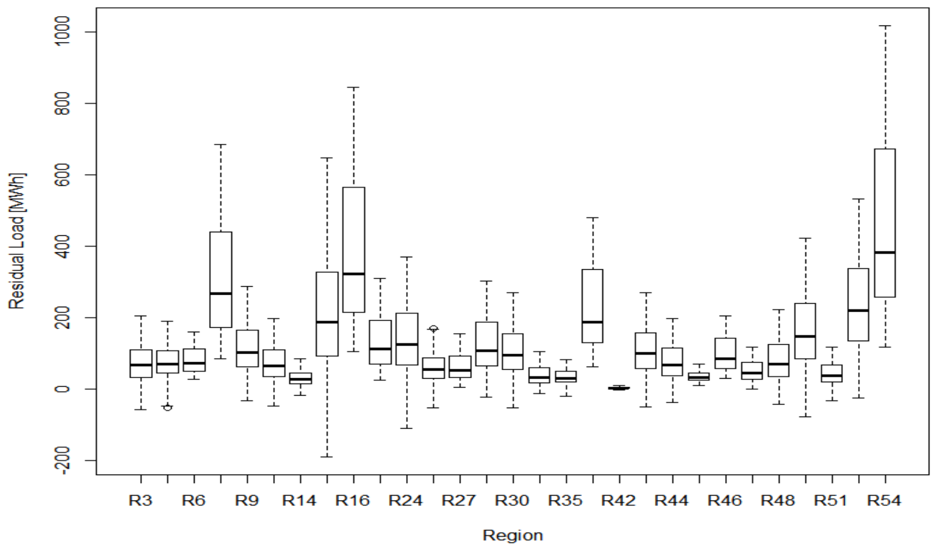



***Figure 28:*** *Boxplot of Residual load with a maximum of 1% Residual Flow; Source: Graph created by the author*

# 5. Discussion and Conclusion

## 5.1. Limitations of the model and opportunities for further research

The applied model is suitable to identify regions in Austria where potential wind power deployment could cause large amounts of surplus electricity or where the additional installed capacities are likely to be consumed within the region. If and to which extent the potential wind power sites would cause strains on the transmission grid is subject to further research. The applied modeling of residual loads is a very simple depiction of reality. There is still substantial potential to further increase accuracy and validity.

The research can be improved by a more accurate modeling of production and consumption data which was provided by others to me. Especially the commercial consumer data has a high potential of improvement since the modeling was done only for small scale businesses but the commercial electricity load should represent the whole industry. Therefore, a large calibration factor was needed.

The potential power production is very optimistic with an average capacity factor of about 2,600 full load hours. Wind turbines in Austria have approximately 1,800 full load hours (“E-Control” 2013). Adjusting the potential wind power production to a more realistic capacity factor would probably increase the accuracy of the model. On the other hand, 2 MW turbines were used for power output calculations but 3 MW turbines already entered the market resulting in a higher yield per wind farm.

The production and load data were not continuously available for the same 12 months of modeling period, so for 3 months in 2011 production data from the same time in 2009 has been used.

For the division of Austria into regions, the distance to substations defines the respective borders. Most commonly wind farms feed into the mid-voltage grid system, so grid nodes at this voltage level would be more suitable for regional division. Furthermore, allocation of consumers to grid nodes using distance as sole criterion is a very rough approach. Unfortunately, detailed grid data is not publically available which makes a more detailed assessment impossible. Another limitation of this model is, with respect to regional load balance, that only potential wind power production is brought into account. Existing electricity production (conventional and renewable) is not considered.

To quantify strains on transmission grids caused by increasing wind power deployment, further research needs to be conducted which includes location and capacity of power lines and electricity production from other sources.

## 5.2. SUMMARY AND DISCUSSION OF RESULTS

A spatially explicit model is applied to analyze to which extent wind power could be expanded in Austria without the need of significant upgrades to the transmission power grid. Austria was divided into regions and the potential wind power production and electricity consumption was aggregated in order to calculate the residual load within these regions. In the scenarios, different possibilities of wind power deployment are assessed by calculating the overall costs, installed capacities, regional residual loads and supra-regional power flows.

Potential wind power sites were used to their maximum to identify regions in which additional WPP could cause a negative residual load and consequently supra-regional power flows. The results show that the Weinviertel (Region 3) and Northern Burgenland (Region 14) have the highest additional installed capacities and the largest surplus electricity production. Western Carinthia and areas East of Vienna could also cause a big amount of supra-regional power flow. In Vorarlberg, Salzburg and Upper Austria the potential installed capacities are so little that supra-regional power flow is negligible in all scenarios. Only two small potential wind power sites are located in Upper Austria, despite their large technical wind power potential (compare figure 4), which means that a guaranteed feed-in tariff of 9.7 c/kWh is not sufficient enough to trigger investments.

The ambitious goal of energy self sufficiency and therefore a wind power contribution of additionally 11.5 TWh to the energy mix is depicted in two scenarios. In the Wind Cost Minimized scenario, the wind power expansion results in a full exploitation of wind turbines in the Weinviertel with 1245 installed wind turbines. The complete exploitation of wind power would likely cause severe interference with the landscape scenery and the electricity production only in Region 3 would cause an annual surplus of 5,961 GWh. So far, Lower Austria has a wind power capacity of 679 MW and an expansion of 2,490 MW would very likely require major invests in the power grid systems.

At the time of writing this thesis, Lower Austria introduced a wind power zone plan which significantly reduces the wind power potential due to legal constraints. Therefore, such a massive expansion in the Weinviertel like in the Wind Cost Minimized scenario is not likely. However, this scenario shows that when economic factors are the main priority for site selection, a locally highly concentrated wind power expansion may occur.

Necessary transmission grid investments will be paid by the grid operator and in consequence by the consumers. Investors in wind parks do not bear costs for the transmission grid. This implies that single, most-windy regions get expanded to their full extent before using alternative sites. There is no incentive in the current form of subsidies for choosing alternative sites in order to enhance the functioning of the whole electrical system. This trend is already notable in Germany where the major wind power production in the North needs to be transferred to the South.

Minimizing the negative residual load – like in the Power Flow Minimized scenario – leads to only 5.7% extra costs and lowers the supra-regional power flow by 58% at the same level of annual production. The reasons for the higher expenses are higher average construction costs per wind turbine of around one percent. Additionally, 96 additional wind turbines are needed to produce the same amount of energy as in the Wind Costs Minimized scenario. Also in this scenario region 3 has the highest share of negative residual load of 85.1% but in total values it is only around a ninth of the first scenario (694 MWh).

Furthermore, wind turbines would be more evenly distributed over Austria in scenario 2 which smoothes out the total power output as seen in figure 24 and discussed by Degeilh and Singh (2011), Beaudin et al.( 2010) and Roques, Hiroux, and Saguan (2010). This is beneficial for the power system when it comes to demand and supply leveling. Especially the peak power outputs could be reduced and the standard deviation is around 17% smaller as in the Wind Costs Minimized scenario.

The Limited Power Flow scenario shows that only small wind power expansions (around 1000 MW) would be possible without supra-regionally transferring electricity. These expansions would be reached in a very short time considering the annual capacity growth rates of roughly 300 MW in the latest years. The stochastic nature of wind and the predicted growth of wind power make transmission power grids probably essential for a stable electricity system.

The research carried out for this master thesis indicates that improving wind power expansion planning, allowing little additional investment costs and considering the local electricity demand, reduces the supra-regional electricity flows significantly. Therefore, it may reduce the stress on the transmission power grid, which would be very beneficial for the electricity system. But the policy measures which are currently in place do not take into account the spatial distribution of the generators. Not at all considering this highly significant aspect is a serious flaw in the subsidy system, which thus should be carefully examined and revised.

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# APPENDIX

## WIND POWER SITE ATTRIBUTES

| Wind Farm | Name | Longitude | Latitude | Investment costs [million €] | Turbines | CAP [MW] | Euro/Turbine [million €] | Allocated Substation |
|---|---|---|---|---|---|---|---|---|
| 1 | STIFT ZWETTL | 15,20361111 | 48,61777778 | 6,94 | 2 | 4 | 3,4685 | 30 |
| 2 | GARS/KAMP | 15,66777778 | 48,59555556 | 237,74 | 67 | 134 | 3,5484 | 4 |
| 3 | LEISER BERGE | 16,37166667 | 48,55888889 | 692,37 | 199 | 398 | 3,4792 | 3 |
| 4 | MISTELBACH (OE3) | 16,61 | 48,57083333 | 1.487,47 | 425 | 850 | 3,4999 | 3 |
| 5 | POYSDORF-OST | 16,6375 | 48,66916667 | 171,04 | 49 | 98 | 3,4905 | 3 |
| 6 | BAERNKOPF | 15,00277778 | 48,39111111 | 10,34 | 3 | 6 | 3,4480 | 30 |
| 7 | JAUERLING/ORF | 15,34027778 | 48,335 | 13,81 | 4 | 8 | 3,4513 | 48 |
| 8 | KREMS | 15,62138889 | 48,41833333 | 10,60 | 3 | 6 | 3,5346 | 6 |
| 9 | LANGENLOIS | 15,6975 | 48,4725 | 14,14 | 4 | 8 | 3,5356 | 4 |
| 10 | STOCKERAU | 16,1925 | 48,39694444 | 236,62 | 68 | 136 | 3,4797 | 3 |
| 11 | LANGENLEBARN | 16,11805556 | 48,32388889 | 27,67 | 8 | 16 | 3,4589 | 4 |
| 12 | GAENSERNDORF-STADT | 16,71361111 | 48,33777778 | 1.044,36 | 298 | 596 | 3,5046 | 3 |
| 13 | ZWERNDORF | 16,83138889 | 48,33805556 | 720,47 | 206 | 412 | 3,4974 | 3 |
| 14 | RIED IM INNKREIS | 13,475 | 48,21722222 | 3,46 | 1 | 2 | 3,4628 | 16 |
| 15 | AMSTETTEN | 14,89861111 | 48,10805556 | 20,88 | 6 | 12 | 3,4808 | 30 |
| 16 | ST.POELTEN/LANDHAUS | 15,63111111 | 48,19972222 | 330,94 | 95 | 190 | 3,4836 | 48 |
| 17 | LILIENFELD-TARSCHBERG | 15,5875 | 48,02805556 | 80,86 | 23 | 46 | 3,5156 | 48 |
| 18 | BADEN | 16,23555556 | 48,01138889 | 6,99 | 2 | 4 | 3,4946 | 29 |
| 19 | WIEN/UNTERLAA | 16,41916667 | 48,12472222 | 119,55 | 34 | 68 | 3,5162 | 29 |
| 20 | WIEN-DONAUFELD | 16,43333333 | 48,2575 | 219,05 | 63 | 126 | 3,4770 | 53 |
| 21 | GROSS-ENZERSDORF | 16,55916667 | 48,19972222 | 827,68 | 237 | 474 | 3,4923 | 50 |
| 22 | SALZBURG-FREISAAL | 13,05333333 | 47,79055556 | 3,55 | 1 | 2 | 3,5539 | 16 |
| 23 | WAIDHOFEN/YBBS-ZENTRUM | 14,78444444 | 47,95777778 | 157,82 | 45 | 90 | 3,5072 | 30 |
| 24 | LUNZ AM SEE | 15,0675 | 47,85444444 | 21,81 | 6 | 12 | 3,6358 | 30 |
| 25 | PUCHBERG/SCHNEEBERG | 15,90694444 | 47,79027778 | 13,94 | 4 | 8 | 3,4848 | 24 |
| 26 | HOHE WAND/HOCHKOGELHAUS | 16,035 | 47,82222222 | 27,79 | 8 | 16 | 3,4741 | 24 |
| 27 | WR.NEUSTADT/FLUGPLATZ | 16,23138889 | 47,83222222 | 245,88 | 70 | 140 | 3,5125 | 24 |
| 28 | GUTENSTEIN/MARIAHILFBERG | 15,87611111 | 47,87138889 | 42,10 | 12 | 24 | 3,5087 | 24 |
| 29 | EISENSTADT-NORDOST | 16,53861111 | 47,85416667 | 176,01 | 50 | 100 | 3,5202 | 51 |
| 30 | SEIBERSDORF | 16,505 | 47,97638889 | 268,11 | 77 | 154 | 3,4819 | 51 |
| 31 | NEUSIEDL AM SEE | 16,84166667 | 47,95083333 | 2.673,38 | 756 | 1512 | 3,5362 | 14 |
| 32 | ANDAU | 17,03333333 | 47,7725 | 1.516,00 | 424 | 848 | 3,5755 | 14 |
| 33 | KUFSTEIN | 12,16277778 | 47,57527778 | 7,28 | 2 | 4 | 3,6385 | 46 |
| 34 | ST.WOLFGANG | 13,45277778 | 47,73694444 | 21,75 | 6 | 12 | 3,6249 | 8 |
| 35 | WINDISCHGARSTEN | 14,32611111 | 47,72027778 | 32,66 | 9 | 18 | 3,6284 | 47 |
| 36 | PRAEBICHL | 14,95416667 | 47,52166667 | 21,10 | 6 | 12 | 3,5163 | 9 |
| 37 | AFLENZ | 15,24083333 | 47,54583333 | 116,73 | 32 | 64 | 3,6479 | 9 |

| Wind Farm | Name | Longitude | Latitude | Investment costs [million €] | Turbines | CAP [MW] | Euro/Turbine [million €] | Allocated Substation |
|---|---|---|---|---|---|---|---|---|
| **38** | RAX/SEILBAHNBERGS TATION | 15,7786111 | 47,7175 | 14,62 | 4 | 8 | 3,6555 | 24 |
| **39** | MOENICHKIRCHEN | 16,03333333 | 47,51111111 | 457,94 | 131 | 262 | 3,4958 | 24 |
| **40** | HIRSCHENKOGEL | 15,83333333 | 47,62333333 | 104,13 | 29 | 58 | 3,5908 | 24 |
| **41** | REUTTE | 10,71527778 | 47,49444444 | 17,54 | 5 | 10 | 3,5076 | 27 |
| **42** | INNSBRUCK-FLUGPLATZ | 11,35666667 | 47,26 | 10,85 | 3 | 6 | 3,6165 | 41 |
| **43** | HAHNENKAMM-EHRENBACHHOEHE | 12,36194444 | 47,41916667 | 3,66 | 1 | 2 | 3,6640 | 46 |
| **44** | BISCHOFSHOFEN | 13,22111111 | 47,40666667 | 14,65 | 4 | 8 | 3,6635 | 23 |
| **45** | ST.VEIT IM PONGAU | 13,15527778 | 47,34694444 | 10,83 | 3 | 6 | 3,6095 | 23 |
| **46** | SECKAU | 14,77944444 | 47,27083333 | 32,42 | 9 | 18 | 3,6021 | 9 |
| **47** | KALWANG | 14,75972222 | 47,42138889 | 17,68 | 5 | 10 | 3,5362 | 9 |
| **48** | ST.MICHAEL B. LEOBEN | 15,00555556 | 47,33583333 | 17,54 | 5 | 10 | 3,5084 | 9 |
| **49** | FISCHBACH | 15,64388889 | 47,44416667 | 236,50 | 67 | 134 | 3,5299 | 43 |
| **50** | HARTBERG | 15,97861111 | 47,28055556 | 7,14 | 2 | 4 | 3,5681 | 44 |
| **51** | BAD TATZMANNS-DORF (OE3) | 16,225 | 47,33805556 | 13,90 | 4 | 8 | 3,4756 | 44 |
| **52** | LUTZMANNSBURG | 16,64555556 | 47,46527778 | 242,51 | 69 | 138 | 3,5147 | 44 |
| **53** | BRAND | 9,738333333 | 47,10305556 | 43,05 | 12 | 24 | 3,5872 | 33 |
| **54** | NEUSTIFT/MILDERS (MT) | 11,29194444 | 47,10277778 | 135,81 | 38 | 76 | 3,5739 | 35 |
| **55** | PATSCHERKOFEL | 11,46166667 | 47,20972222 | 21,53 | 6 | 12 | 3,5883 | 41 |
| **56** | KRIMML | 12,1825 | 47,23277778 | 7,40 | 2 | 4 | 3,7000 | 42 |
| **57** | VIRGEN | 12,45583333 | 47,00277778 | 10,89 | 3 | 6 | 3,6291 | 13 |
| **58** | RAURIS | 12,9925 | 47,22361111 | 3,49 | 1 | 2 | 3,4876 | 45 |
| **59** | SONNBLICK (TAWES) | 12,9575 | 47,05416667 | 3,50 | 1 | 2 | 3,5050 | 13 |
| **60** | OBERTAUERN | 13,55972222 | 47,24861111 | 21,53 | 6 | 12 | 3,5881 | 26 |
| **61** | KATSCHBERG | 13,61472222 | 47,06027778 | 443,23 | 123 | 246 | 3,6035 | 13 |
| **62** | MARIAPFARR | 13,745 | 47,15194444 | 53,75 | 15 | 30 | 3,5836 | 26 |
| **63** | MURAU | 14,17694444 | 47,11111111 | 193,89 | 54 | 108 | 3,5906 | 26 |
| **64** | NEUMARKT | 14,42472222 | 47,06972222 | 156,81 | 43 | 86 | 3,6468 | 15 |
| **65** | ZELTWEG | 14,75972222 | 47,20138889 | 10,93 | 3 | 6 | 3,6430 | 9 |
| **66** | KOEFLACH (OE3) | 15,08722222 | 47,07 | 32,88 | 9 | 18 | 3,6529 | 54 |
| **67** | SCHOECKL | 15,46638889 | 47,19861111 | 3,71 | 1 | 2 | 3,7110 | 43 |
| **68** | GALTUER | 10,18555556 | 46,96777778 | 3,58 | 1 | 2 | 3,5845 | 33 |
| **69** | DOELLACH | 12,90361111 | 46,95861111 | 3,59 | 1 | 2 | 3,5918 | 13 |
| **70** | MALLNITZ | 13,1675 | 46,9925 | 10,74 | 3 | 6 | 3,5793 | 13 |
| **71** | OBERVELLACH | 13,22333333 | 46,92888889 | 3,75 | 1 | 2 | 3,7550 | 13 |
| **72** | MILLSTATT | 13,57361111 | 46,80833333 | 150,12 | 41 | 82 | 3,6615 | 13 |
| **73** | SPITTAL/DRAU | 13,48722222 | 46,79055556 | 18,04 | 5 | 10 | 3,6072 | 13 |
| **74** | ST.ANDRAE/LAVANTT AL | 14,82805556 | 46,76416667 | 117,81 | 32 | 64 | 3,6816 | 15 |
| **75** | PREITENEGG | 14,915 | 46,93805556 | 77,44 | 21 | 42 | 3,6876 | 15 |
| **76** | DELLACH | 13,08277778 | 46,74194444 | 47,91 | 13 | 26 | 3,6853 | 13 |
| **77** | KANZELHOEHE | 13,90194444 | 46,67722222 | 10,76 | 3 | 6 | 3,5879 | 15 |
| **78** | ARRIACH | 13,8525 | 46,72777778 | 361,30 | 101 | 202 | 3,5772 | 15 |
| **79** | FELDKIRCHEN | 14,09694444 | 46,72194444 | 145,96 | 41 | 82 | 3,5600 | 15 |

# Substation Attributes

| Substation / Region Nr. | Name | Longitude | Latitude |
|---|---|---|---|
| **3** | OBISAM1 | 16,37861 | 48,3575 |
| **4** | ODUERN1 | 15,8825 | 48,32917 |
| **5** | OERNST11 | 14,47361 | 48,12556 |
| **6** | OETZER1 | 15,73667 | 48,26861 |
| **8** | OHAUSR2 | 13,89944 | 48,10389 |
| **9** | OHESSE2 | 15,02056 | 47,39667 |
| **13** | OLIENZ1 | 12,80528 | 46,82472 |
| **14** | ONEUSI2 | 16,83778 | 47,96028 |
| **15** | OOBERS22 | 14,68139 | 46,66833 |
| **16** | OPETER2 | 13,08083 | 48,25611 |
| **23** | OTAUER1 | 12,73972 | 47,27778 |
| **24** | OTERNI23 | 16,06444 | 47,70722 |
| **26** | OWEISS2 | 14,20806 | 47,57389 |
| **27** | OWESTT2 | 10,87361 | 47,24417 |
| **28** | OWIEN 1 | 16,33028 | 48,16528 |
| **29** | OWIEN 2 | 16,41806 | 48,12194 |
| **30** | OYBBSF2 | 15,04806 | 48,14583 |
| **31** | OZELL1 | 11,89806 | 47,23333 |
| **33** | Bludenz | 9,810278 | 47,14278 |
| **34** | Dornbirn | 9,716944 | 47,4325 |
| **35** | Eigenhofen | 11,21444 | 47,27917 |
| **36** | Mayrhofen | 11,85056 | 47,1625 |
| **37** | Meiningen | 9,591667 | 47,31222 |
| **38** | Rosshag | 11,77833 | 47,08528 |
| **39** | Silz | 10,96639 | 47,26944 |
| **40** | Strass | 11,83861 | 47,39222 |
| **41** | Thaur | 11,47139 | 47,27278 |
| **42** | Häusling | 11,9675 | 47,14611 |
| **43** | Gleisdorf | 15,7225 | 47,09139 |
| **44** | Grosspetersdorf | 16,27611 | 47,25056 |
| **45** | Kaprun | 12,74222 | 47,25917 |
| **46** | Kirchbichl | 12,07611 | 47,52222 |
| **47** | Klaus | 14,16306 | 47,82111 |
| **48** | Pottenbrunn | 15,68917 | 48,22472 |
| **49** | Reitersdorf | 14,53889 | 48,24056 |
| **50** | Simmering | 16,43389 | 48,18139 |
| **51** | Sixtneusiedl | 16,69556 | 48,03194 |
| **52** | Wien-Kendlergasse | 16,31111 | 48,20528 |
| **53** | Wien-Nord | 16,39 | 48,2575 |
| **54** | Zwaring-Pöls | 15,42306 | 46,90361 |

## Computer Codes

### Auxiliary variable

```
lproduzenten <- length(produzenten[,1])          ##Number of  wind farms
lsubst <- length(subst[,1])                      ##Number of substations
lproduktion <- length(produktion[,1])            ##Hours of production
lcomkoord <- length(comkoord[,1])         ##Numbers of commercial Consumers (grid)
lhhkoord <- length(hhkoord[,1])           ##Number of houshold comsumers (grid)

nameumspann<-vector(mode="character", length=length(produzenten[,1]))

prodzuu<-vector(mode="integer", length=length(produzenten[,1]))

comzuu<-vector(mode="integer", length=length(comkoord[,1]))

 hhzuu<-vector(mode="integer", length=length(hhkoord[,1]))

distanzen<-vector(mode="integer", length=length(subst[,1]))

## Matrix für die Produktionssumierung der Umspannwerke
sumprod<-matrix(nrow = 17522, ncol = 79,data=0)
## Matrix für den Kommerziellen Load summiert nach Umspannwerken/// 500->Zwischenspeicher für
fetch(), anschließend in DB gespeichert
sumcom<-matrix(nrow = 500, ncol = 79,data=0)
```

### Function for distance calculations

```
geodetic <- function(x,y)   {                     ##x=long, y=lat
        R <- 6371

        point1<- matrix(c(x,y),1)
        p1rad <- point1 * pi/180

        p2rad <- subst[,-3] * pi/180

        for(i in 1:length(subst[,1]))        {

                d <- sin(p1rad[1,2])*sin(p2rad[i,2])+cos(p1rad[1,2])*
                cos(p2rad[i,2])*cos(abs(p1rad[1,1]-p2rad[i,1]))
                 d <- acos(d)
                 distanzen[i]<-R*d

                                             }
        return(which(distanzen == min(distanzen))
                            }
```

### Allocation of wind farms to substations

```
for(i in 1:lproduzenten)    {

        prodzuu[i]<-geodetic(produzenten[i,2],produzenten[i,3])

        nameumspann[i]=subst[prodzuu[i],3]
                            }
```

```
Produmspann<-cbind(produzenten,prodzuu,nameumspann)

for(i in 1:lproduzenten) produktion[1,i+1]<-trunc(prodzuu[i])
```

**Allocation of commercial consumers to substations**

```
for(i in 1:lcomkoord)        {
          comzuu[i]<-geodetic(comkoord[i,4],comkoord[i,5])
                              }
comkoord<- cbind(comkoord,comzuu)
```

**Allocation from household consumers to substations**

```
for(i in 1:lhhkoord)          {
          hhzuu[i]<-geodetic(hhkoord[i,5],hhkoord[i,4])
                              }
hhkoord<- cbind(hhkoord,hhzuu)
```

**Converting household and commercial data from 15 min into 1h time resolution**

```
bulk<-1000                          ## Number of how many lines should be read form 'res' at once

while(!dbHasCompleted(resCom15min))     {

           data15min <- fetch(resCom15min, n = bulk)

           for(i in 1:250)     {
                    a<-i*4-3
                    b<-i*4
                   data1h[i,]<-colMeans(data15min[a:b,])
                    data1h<-as.data.frame(data1h)
                   dbWriteTable(con = dbCom, name = " Commercialshours ", value = data1h ,row.names
                   = FALSE, header = FALSE,append=TRUE

                              }

                                                  }
```

**Aggregation of wind farm production to the allocated regions**

```
sumprod<-matrix(nrow = lproduktion, ncol = lsubst,data=0)

for(i in 1:lproduzenten)     {

           for(m in 1:lsubst)           {



           if(produktion[1,i]==m)                 {
                   sumprod[1:(lproduktion-1),m]<-sumprod[1:(lproduktion-1),m]+
                             produktion[2:lproduktion,i]

                                                  }

                                        }
                              }
```

**Aggregation of commercial loads to the allocated regions**

```
resh <- dbSendQuery(dbein, "SELECT * from Commercialshours ")

while(!dbHasCompleted(resh))      {
          data<- fetch(resh, n = 500)
          datakopf<-rbind(comzuu,data

          summe<-matrix(nrow = 500, ncol = 54,data=0)

          for(i in 1:lcomkoord)                  {

                    for(m in 1:lsubst)                        {


                              if(datakopf[1,i]==m)                    {

                                        summe[1:500,m]<-summe[1:500,m]+datakopf[2:501,i]
                                                                      }

                                                              }
                                                       }

          summe<-as.data.frame(summe)
          dbWriteTable(con = dbsumme, name = "LoadComSum", value = summe ,row.names = FALSE,
          header = FALSE,append=TRUE)
                                        }
```

**Aggregation of household loads to the allocated regions**

```
resh <- dbSendQuery(dbein, "SELECT * from Householdhours A") ## import of Houshold
                                        ##Load ( resolution h, for the first 25000 columns)
                                        ## database HouseholdhoursB for the following 25000 columns
while(!dbHasCompleted(resh))      {
          data<- fetch(resh, n = 500)
          datakopf<-rbind(hhzuu[1:25000],data)
                                        ## hhzuu[25001: 49458] for the database HouseholdhoursB
          summe<-matrix(nrow = 500, ncol = 54,data=0)

          for(i in 1:25000)                      {     ## resp.. 25001:49458

                    for(m in 1:lsubst)                        {


                              if(datakopf[1,i]==m)                    {
                                        summe[1:500,m]<-summe[1:500,m]+datakopf[2:501,i]
                                                                    }

                                                              }
                                                       }

          summe<-as.data.frame(summe)
          dbWriteTable(con = dbsumme, name = "LoadHHSumA", value = summe ,row.names = FALSE,
          header = FALSE,append=TRUE)
                                        }
```

**Export of aggregated loads**

```
res <- dbSendQuery(dbsumme, "SELECT * from LoadHHSumA")
resb <- dbSendQuery(dbsumme, "SELECT * from LoadHHSumB")
resc <- dbSendQuery(dbsumme, "SELECT * from LoadComSum")

temp <- fetch(res, n = -1)
tempb <- fetch(resb, n = -1)
tempc <- fetch(resc, n = -1)

temp=temp[-9481:-10000,]
tempb=tempb[-9481:-10000,]
tempc=tempc[-9481:-10000,]

SumHH<-temp+tempb
write.csv(SumHH,file="HHSum.csv")
write.csv(tempc,file="ComSum.csv")
```