Wind Energy and Repowering Potential in Rhineland-Palatinate from 2021 to 2030

Master's Thesis submitted

to

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Contents

Abstract

This is the template for a thesis at the Chair of Econometrics of Humboldt–Universit"at zu Berlin. A popular approach to write a thesis or a paper is the IMRAD method (Introduction, Methods, Results and Discussion). This approach is not mandatory! You can find more information about formal requirements in the booklet 'Hinweise zur Gestaltung der Ã¤uÃŸeren Form von Diplomarbeiten' which is available in the office of studies.

The abstract should not be longer than a paragraph of around 10-15 lines (or about 150 words). The abstract should contain a concise description of the econometric/economic problem you analyze and of your results. This allows the busy reader to obtain quickly a clear idea of the thesis content.

List of Abbreviations

IPCC	Intergovernmental Panel on Climate Change	GHG	Greenhouse gas
ROI	Region of interest	mm	Million
RLP	Rhineland-Palatinate	TWh	Tera Watt hours
WT	Wind turbine	MWh	Mega Watt hours
kWh	Kilo Watt hours	GIS	Geographic Information System
MaStR	Market master data register	EEG	Renewable Energy Act
kg	Kilogram	m	Meter
s	Second	W	Watt
d	Diameter	m^2	Square meter
m^3	Cubic meter	DWG	German Wind Guard
CRS	Coordinate Reference System	WGS84	World Geodetic System 1984

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1 Introduction

This work was executed and written in scientific recognition of the importance of reducing greenhouse gas emissions and expanding renewable energies to mitigate the effects of climate change.

This study was also carried out on behalf of the state-owned Energy Agency of Rhineland-Palatinate [1] within the project "Municipal Greenhouse Gas Accounting and Regional Climate Protection Portals in Rhineland-Palatinate" [2], which is funded by the European Regional Development Fund [3] and the state of Rhineland-Palatinate (RLP). This project supports the creation of municipal climate protection measures in order to mitigate CO_2 emissions and achieve the climate protection goals of the municipalities and the state and thereby increases regional added value, ensures sustainability and thus improves the quality of life of all citizens. The state act to promote climate protection (State Climate Protection Act - LKSG -) came into force on 23 August 2014 and states that the total of all greenhouse gas emissions in Rhineland-Palatinate have to be reduced by at least 40% by 2020 compared to the base year 1990. Further the aim is to reduce greenhouse gas emissions by 100% by 2050, but at least by 90% [4]. More pressure comes from the recent press release No. 31 from April 29, 2021 [5] of the first Senate of the Federal Constitutional Court in which is stated that the regulations of the Climate Protection Act December 12, 2019 [6] on the national climate protection targets and the annual emission quantities permitted up to 2030 are incompatible with fundamental rights, as there are no sufficient criteria for further emission reductions from 2031 onward. It is stated that the legal requirements are not sufficient to bring about a timely transition to climate neutrality. The German legislature has therefore published an adjusted edition of this act that strives for a faster development of renewable energies and the energy transition in general [7]. Likewise the coalition agreement from 2021 to 2026 of the current government of RLP desires the goal of "100% renewable energies by 2030" and it can be assumed that the Climate Protection Act will be amended. This shows that this study is very topical and also highly embedded in a dynamic socio-economic context [8]. Thus, the energy transition is regarded as a cornerstone of the strategy to climate neutrality and RLP wants to play a pioneering role in the implementation of the energy transition . In addition to energy from the sun, water and biomass, two thirds of the electricity generated in 2030 should come from wind power and is therefore the subject of this master thesis [9].

As of 2017, the gross electricity generation in RLP from wind power was 5.9 TWh, which was 29% of the total 20.7 TWh of electricity generated in the state [10]. By 2019, the electricity generated from wind turbines (WTs) has already increased to more than 6.7 TWh [11]. It can be assumed that, on the one hand, electricity consumption will increase in the future due to the electrification of transport and domestic heating, and on the other hand, efficiency measures can also lead to a lower energy consumption. Whereas, some past studies and scenarios estimated a slight increase and others a slight decrease but on average a relatively unchanged electricity consumption in Germany, which is currently about 560 TWh [12], the newest press release of the Federal Ministry for Economic Affairs and Energy makes it very clear. An increase to a previous prediction of about 12% from 580 to 655 TWh is expected [13], and further studies will follow in the autumn of 2021. If RLP wants to become independent of electricity imports and achieve the self-set goals of covering two thirds of the electricity consumption from wind power with an estimated electricity demand of 33 TWh in 2030, electricity supply from WTs must be about 22 TWh per year. There are two ways of increasing the amount of electricity generated by wind energy. Either areas can be used that have already been identified as suitable for WTs but have not yet been built on, or else, existing old systems whose absolute electricity feed-in quantity is low, can be replaced by new, taller and more efficient systems through the so-called "repowering."

The aim of this work is to develop a method for calculating the wind energy potential and its related area consumption at a state level regarding the two described options. The objective is then to evaluate the desired expansion and emission reduction targets up to 2030 and assess weather they are realistic and in line with the current distance rules and approval procedures and give recommendations for policy makers. Accordingly, the central three questions of this work are:

1. How much electricity can be generated by a new WT from 2021 until 2030 in RLP per area?

2. What is the potential when all wind turbines with built before 2005 are repowered?

3. How much area is needed to generate the target amount of 22 TWh?

In order to answer these questions the data analysis and results of the master and movement data provided by the transmission system operator Amprion and of the market master data register (Marktstammdatenregister - MaStR) is Presented in chapter 3 and 4. The gained results are discussed subsequently in chapter 5 and the paper ends with a summary of the main findings and a recommendation to policy makers in the concluding chapter number 6. To introduce the reader with all the necessary background information on the topic, the scientific and technical fundamentals, that are a prerequisite to this thesis and the assessment of the electricity yield from onshore WTs in RLP, are explained in the following chapter number 2.

2 State of the art

2.1 Greenhouse gas emissions

First of all, the problem of greenhouse gas emissions will be stated briefly as the bases and motivation of this thesis. It is getting warmer, as Ed Hawkins a climate scientist from the University of Reading impressively visualizes with his warming stripes using the World Meteorological Organization (WMO) annual global temperature data set (Figure 1). The color of each stripe, in which blue indicates cooler and red warmer temperature, represents the anomaly to the average annual temperature in the period of 1971 - 2000.

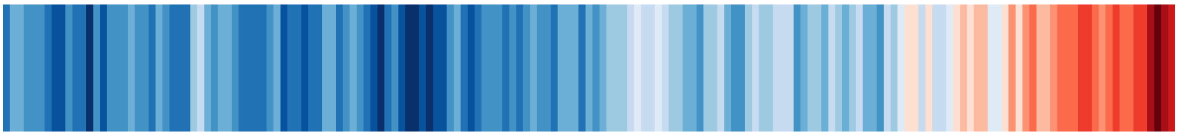

Figure 1: Warming stripes for 1850-2018 using the WMO annual global temperature data set [14].

The debate about the significance of global warming and climate change is already omnipresent in social media, newspapers, politics, economics and science, as well as the society as a whole, and its relevance is still growing. The Intergovernmental Panel on Climate Change (IPCC) has brought virtually unequivocal evidence that the increase of average global temperature is related to anthropogenic greenhouse gas (GHG) concentrations [15]. The major international project to encounter climate change and adapt to its effects is the Paris Agreement, whose central aim is to minimize the threat of climate change by keeping the global temperature increase well below 2 °C preferably below 1.5 °C of the pre-industrial level [16]. The Paris Agreement requires all 196 participating countries to proclaim their according efforts through Nationally Determined Contributions. After missing several targets, Germany passed the Climate Protection Law in December 2019. The climate protection targets for 2030 are set to reduce GHG emissions by at least 55% compared to 1990. The law also formulates the goal of GHG neutrality by 2050. The biggest GHG emitter in Germany is the energy industry [17]. Consequently, to reduce its GHG emissions in the energy sector and to support the development of renewable energy power plants, Germany implemented the Renewable Energy Sources Act in 2000 with latest editions from 2017 and 2021. This law intends to support the expansion of renewable energies with the aim of 65% of electricity from renewable sources in 2030. This should be done by regulating the preferred feed-in of electricity from renewable energy sources (RES), mainly wind and sun, into the power grid as well as ensuring fixed feed-in tariffs (FIT) for a period of 20 years to ensure the fast expansion of renewable energy power plants and therefore reduce GHG emission and limit global warming [18].

2.2 Region of interest

Secondly, the region of interest (ROI) in this case Rhineland-Palatinate in south-west Germany is presented for it is important to know the site conditions and the statistical parameters of the past to assess the wind energy potential for future years. RLP has diverse geographic structures such as many low mountain ranges and forests namely the Rhenish Slate Mountains, Hunsrück, Eifel, Taunus, Westerwald, North Palatinate Uplands and further south the Palatinate Forest but also plain areas such as the Upper Rhine Plain, Mainz Basin and West Palatinate moorlands to only name a few. It borders North Rhine-Westphalia in the north, Hesse and Baden-Wuerttemberg in the east, the French region of Grand Est and Saarland in the south, and Luxembourg and the province of Liège in the Belgian region of Wallonia in the west. Rhineland-Palatinate is the federal state with the largest area on the left bank of the river Rhine. The climate in Rhineland-Palatinate is characterized by a moderate, humid climate with warm summers and mild to cool winters which makes it a typical Western European climate. The average annual temperature is 10.4 °C which is 1.8 °C above the long-term average. Settlement areas occupy around 8,6 % and transport infrastructure around 6.1 % of the area [19]. Rhineland-Palatinate is one of the most densely forested countries in Germany, as the forests here cover around 42 percent of the country's area [20].

Especially the electricity generation and data from existing WTs is important but also information about different types of land cover and the occurrence of wind are crucial for this work. An overview of important parameters regarding the estimation of the wind energy potential up to the year 2030 are shown in table 1.

Basic information on Rhineland-Palatinate	
Area	**19,858 km²**
Agricultural area	**8,110 km²**
Forest area	**8,060 km²**
Settlement and traffic areas	**2,901 km²**
Inhabitants	**4.1 mm**
Electricity demand 2021	**30 TWh**
Electricity demand 2030	**33 TWh**
Electricity generation 2017	**20.7 TWh**
Electricity generation from WTs 2019	**6.78 TWh**
Required generation from WTs in 2030	**22 TWh**
Total number of WTs	**1,702**

Table 1: Important information of Rhineland-Palatinate regarding the assessment of the wind energy potential up to 2030 [19] (rounded)

The study area and the modeled wind speeds taken from the Windatlas RLP [21] are seen in Figure 2.

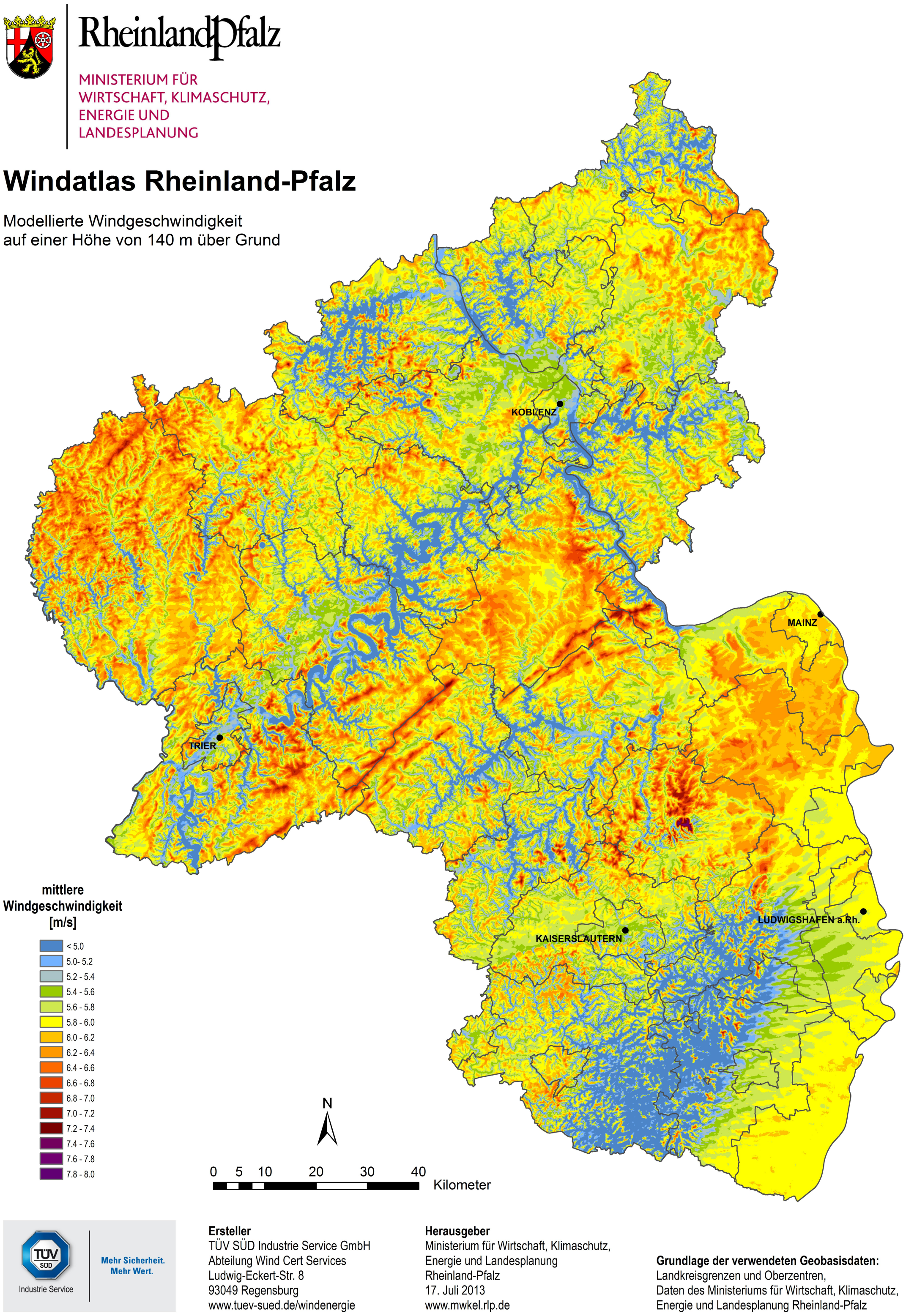

Figure 2: Wind speeds in RLP 140 m above Ground [21].

2.3 Onshore wind turbines and repowering

Wind energy has been used by humans for thousands of years, but the generation of electrical power has only been possible since the 19th century with the beginning of industrialization and is now the subject of constant research and development in the context of the energy transition [22]. A wind turbine usually consists of the three main components: rotor blades, nacelle and tower. In addition to other elements, the nacelle contains: the gearbox, generator, transformer and control system [23]. Most commonly WTs have three rotor blades that are attached to the rotor hub and absorb the kinetic energy of the wind and convert it into a rotary motion. If the winds are too strong, the rotor blades can be “taken out of the wind” by adjusting the blades, thus protecting the system from damage. The gearbox changes the speed of the rotary motion and the generator converts the kinetic energy into electricity. However, there are also systems with direct drive and without gear. The nacelle can be rotated to an optimal position when the wind conditions change, and an electromagnetic brake helps to shut down the system when the winds are too strong or during maintenance work. In addition to its load-bearing function, the tower also contains the power lines that conduct electricity to the grid connection of the distribution network [24].

The transmission system operators, in this case Amprion, are obliged to publish so-called master and movement data for the amount of electricity fed-in with remuneration for each calendar year in accordance with section 77 of the 2017 Renewable Energy Act (EEG) [25]. This master and movement data includes information about the annual electricity generation and the EEG system key. The data for RLP is currently available until 2019. The total amount of electricity fed in with remuneration in 2019 from wind turbines in RLP is 6,782,180,753 kWh, i.e. approximately 6.782 TWh [26].

2.4 Physical basics

The amount of electricity generated by a wind turbine -the electricity yield- can be derived from the physical relationship between the kinetic energy and the power of the wind. Without claiming to be exhaustive, the following applies[1]:

$$E_{kin} = \frac{1}{2} m v^2 \tag{1}$$

The air throughput (mass flow $\hat{m}$) that flows through the area swept by the rotor blades can be calculated by multiplying the air density, rotor area and wind speed as well as the time interval required

[1] $E_{kin} = kinetic\ energy,\ m = mass\ of\ air,\ v = wind\ speed$

with[2]:

$$\hat{m} \; = \; \rho A v t \tag{2}$$

The power P is equal to the energy per unit of time $\hat{E}$. This results in the power of the wind with[3]:

$$P_{wind} \; = \; \hat{E} \; = \; \frac{1}{2}\,\hat{m}v^2 \; = \; \frac{1}{2}\,\rho\pi r^2 v^3 \tag{3}$$

(Mac Kay [27] and BWE [28])

In Formula 3 it becomes clear that the wind speed is the determining factor for the performance of a WT. Because WTs are built to perform at lower wind speeds, most of the time they are not able to operate at very high wind speeds and have to be taken out of the wind at a certain speed to avoid fatigue and destruction through peak loads. A typical load profile of a WT is shown in Figure 3. If the density of air is 1.3 kg/ m³ and there is an average windspeed of 6 m/s, which could be realistic for many sites in RLP at 140 m above ground, as seen in Figure 2, then the typical power of the wind per square meter of rotor area is[4]:

$$\frac{1}{2}\,\rho v^3 \; = \; \frac{1}{2}\,1.3kg/m^3 \; * \; (6m/s)^3 \; = \; 140\;W/m^2 \quad [1\,\frac{kg\,m^2}{s^3} = 1\;W] \tag{4}$$

The curve of power per m^2 in relation to the wind speed is also shown in Figure 3. Of course, not all the wind's power can be converted and there are further losses when converting kinetic energy into electrical energy in the generator. The maximum theoretical efficiency obtained for wind turbines is

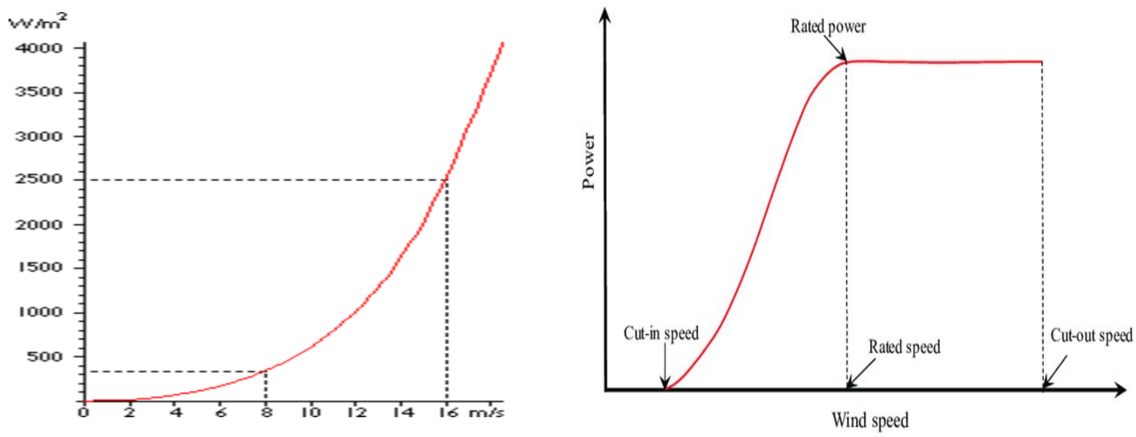

Figure 3: Left: Power of the wind per rotor area over wind speed; Right: Typical load profile of a WT

59% according to the Betz Limit [29]; however, in practice it is often around 40% up to a maximum of

[2] $\rho = density\ of\ air,\ A = rotor\ area,\ t = time$
[3] $r = radius\ of\ rotor,\ \pi = pi$
[4] $W = Watt$

50% [30]. If the average rotor diameter installed in RLP in 2020 is 130 m (Figure 6) with an efficiency of 50%, then the average power of one WT is[5]:

$$
\begin{aligned}
P_{WT} &= 0.5 \ * \ \frac{1}{2}\,\rho v^3 \ * \ \frac{\pi}{4} d^2 \\
P_{WT130} &= 70 \ W/m^2 \ * \ \frac{\pi}{4}(130m)^2 \ = \ 929 \ kW
\end{aligned}
\tag{5}
$$

The amount of energy also increases proportionally with increasing rotor diameter. This explains why the rotor diameters become larger in practice (Figure 6). But WTs with larger rotors have to be spaced further apart. In the literature, values can be found of 3 to 8 times the rotor diameter, depending on the main direction of the wind [27]. If we assume further that WTs in RLP are spaced on average 5 times their diameter apart from each other, from the average power calculated in Equation 5 follows that the energy per area of land is::

$$
\begin{aligned}
\frac{P_{WT}}{m^2} &= \frac{\frac{1}{2}\rho v^3 \ \frac{\pi}{8} d^2}{(5d)^2} \\
&= \frac{\pi}{200} \ \frac{1}{2} \ \rho v^3 \\
&= 0.016 \ * \ 140 W/m^2 \\
&= 2.2 \ W/m^2
\end{aligned}
\tag{6}
$$

This means that independent of the rotor size, there is a limit of around 2.2 W/m^2 of electrical energy that can be delivered in Rhineland-Palatinate assuming an average wind speed of about 6 m/s. In the literature, values for the electric power per area vary from 1 to 7 W/m^2 land area depending on the site conditions [31]. Nonetheless, building taller WTs can be beneficial due to higher and more constant wind speeds with increasing height and other economic factors. As a rough estimate it can be said that doubling the height increases wind speed by 10% and therefore increases the power of the wind by 30%. Thus, the hub heights also tend to increase (Figure 7). The actual way that wind speed increases with height is much more complicated and depends on the roughness of the surrounding area and time and is beyond of the scope of this study. Usually WTs are designed to start operating at wind speeds of around 3 to 5 m/s and stop at around 25 m/s. A WT has a so-called “capacity” or “peak power” which is the maximum power that the WT can generate in optimal conditions. The actual average power that is delivered can be expressed by the capacity multiplied by a factor that describes the fraction of the time that wind conditions are near optimal. This factor is called the “load factor” and as of 2009, a typical load factor was around 19% in Germany, 22% in the Netherlands and 30% in the United Kingdom

[5] $P_{WT} = Power\ of\ a\ WT\ with\ 50\ \%\ efficiency,$
$P_{WT130} = Power\ of\ the\ same\ WT\ with\ rotor\ diameter\ of\ 130\ m$

[27]. Lastly it can be estimated how much area is needed when we assume a constant electricity yield of 2.2 W/m^2 and an electricity demand of 22 TWh per year in RLP:

$$A_{22TWh} \;=\; \frac{22 * 10^{12}\; Wh}{2.2\; W/m^2 \;*\; 8765h \;*\; 10^6} \;=\; 1140.9\; km^2 \tag{7}$$

The total area of RLP is 19,858 km^2, which means that the desired amount of electricity coming from wind energy would be equivalent to covering roughly 5.8 % of the area with WTs. The actual 6.782 TWh of electrical energy generated in RLP would relate to 351.7 km^2 which means that currently about 1.8% of the area of RLP is covered with WTs given the previously defined assumptions are true. If the same calculation for the whole of Germany is done, the demanded 655 TWh in 2030 would need an area of about 33,968 km^2 which is about 9.5 % of the total area. Whereas the area consumption for RLP is still somehow imaginable it is clear that covering nearly 10 % of Germany with WTs is very uncertain. It should also be noted, that the assumption of an average wind speed of 6 m/s could be an under- or overestimate and the area consumption is different in practice. In chapter 3 and 4 the actual numbers for RLP are presented and therefore allow for an evaluation of this theoretical approximation. For further explanation of the technical development and the calculation method, the study of the German Wind Guard (DWG) “full-load-hours of wind turbines on land - development, influences, effects” from October 5th, 2020 [32], is used as a guide and the relevant results are presented in the next subsection.

2.5 Technical concepts and development

The study of DWG examines the development of full-load-hours and thus the wind energy potential in Germany and is divided into the sub-areas Schleswig-Holstein (SH), north (Norden), centre (Mitte) and south (Süden) [32]. RLP is part of the southern region.

The full-load-hours are a measure of the degree of utilization of a power generation plant and denote the time that a plant would have to be operated at nominal load in order to achieve the same power production as it has achieved over the entire reference period with fluctuating generation capacity. The full-load-hours of wind turbines are usually given per calendar year. The full-load-hours per year are calculated from the quotient of the annual energy yield and the nominal output also called as rated capacity. Since the full-load-hours result from the electricity yield and the installed nominal power, there is a dependency and the gain in information is limited. However, knowing the average full-load-hours of all wind turbines and their development is of great importance, as it establishes the connection between installed power and expected energy yield within a certain area. For a forwardlooking political control of the future share of wind energy in the energy transition, an assumption for the full-load-hours to be expected in the future is necessary. The aim of the presented study is to make an assessment of the future development of the full-load-hours of wind turbines on land. Furthermore, it should be estimated what total energy yield is possible with the expected system technology on all designated areas. The development of the full-load-hours in different parts of Germany can be seen in Figure 4. The study of DWG suggests that the wind energy potential, i.e., the theoretical electricity

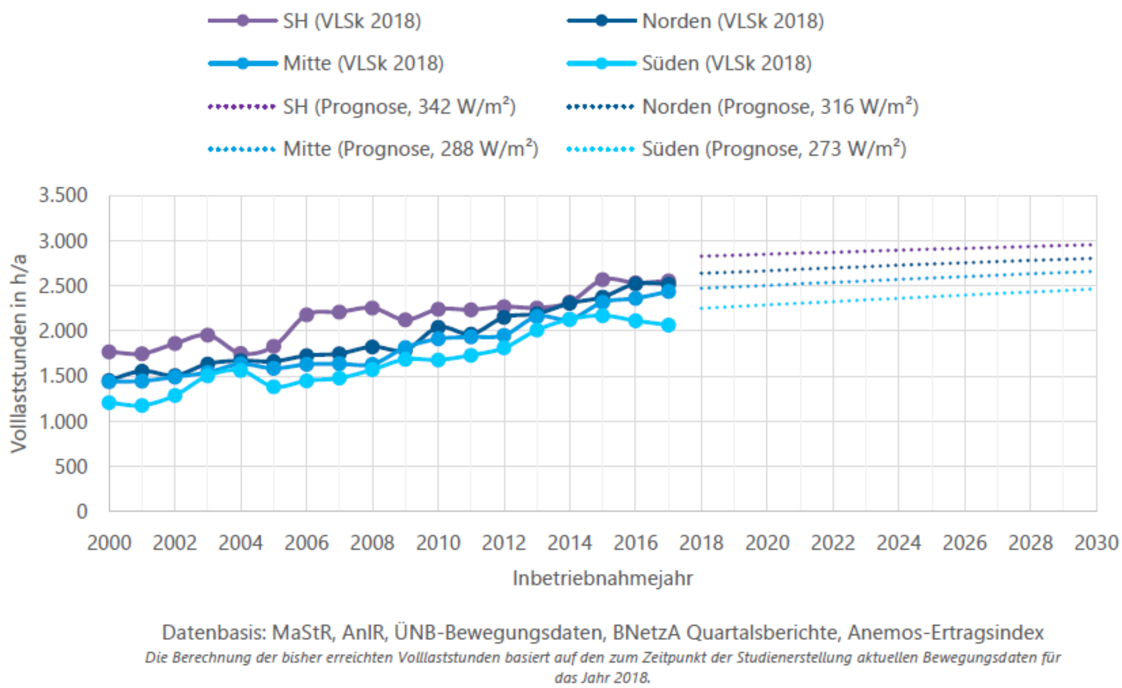

Figure 4: Development and forecast of the mean full-load-hours (in h) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020

yield of a wind turbine for future systems, can be calculated using the following formula:

$$Electricity\ yield\ =\ Full - load - hours\ *\ Capacity$$

The capacity is the installed nominal output, also called rated capacity of the generator and can be found in the technical details of a wind turbine generator. The development of the installed nominal power depending on the commissioning date in Germany can be seen in Figure 5.

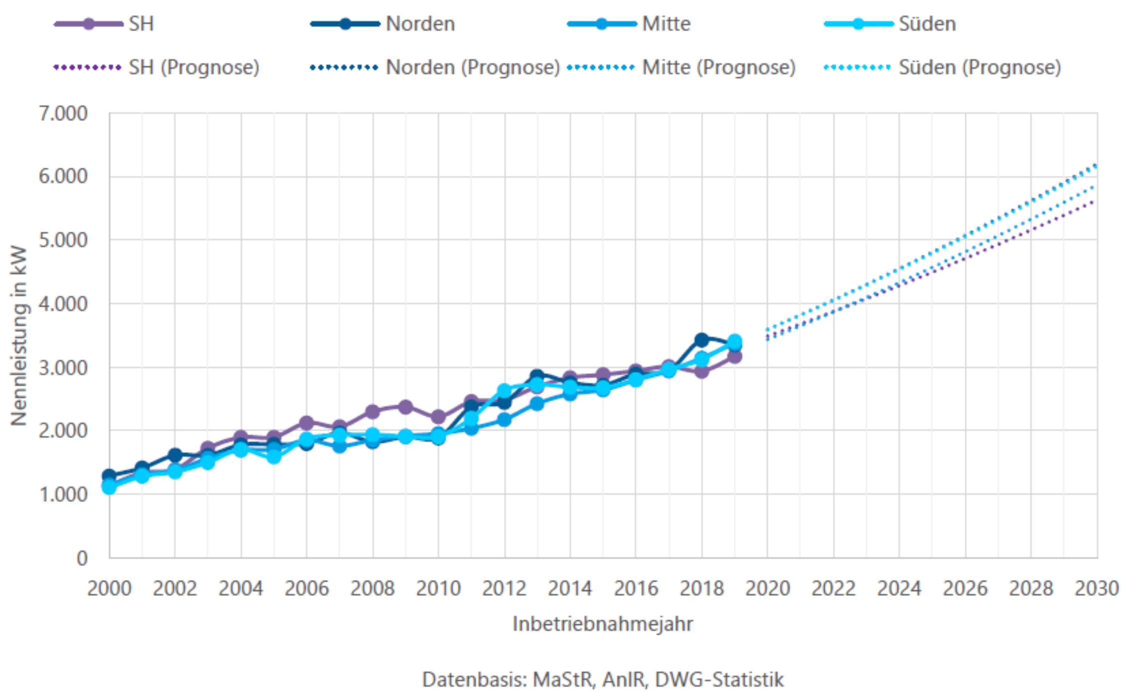

Figure 5: Development and forecast of the mean rated capacity (in kW) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020

With a fixed nominal output, a high full-load hourly value is also associated with a high energy yield. For example, the full load hours achieved by a WT in different years can be compared well with one another in order to make a statement about the electricity yield for a year. However, If two WTs have the same hub height and the same rotor diameter, but a different rated capacity, the less powerful WT, i.e., the WT with the lower specific rated capacity, will achieve more full-load-hours but a lower annual energy yield at the same wind speeds. The full-load-hourly value should therefore always be considered and evaluated in connection with the energy yield. The development of the rotor diameter and hub height is shown in Figure 6 and 7.

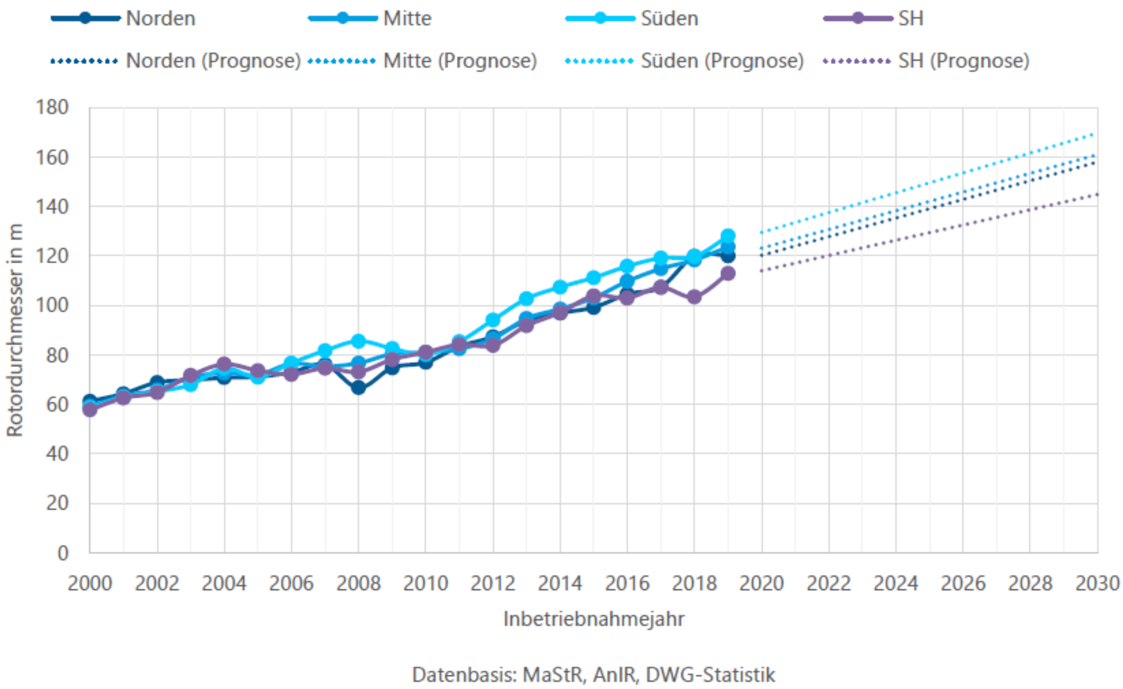

Figure 6: Development and forecast of the mean rotor diameter (in m) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020

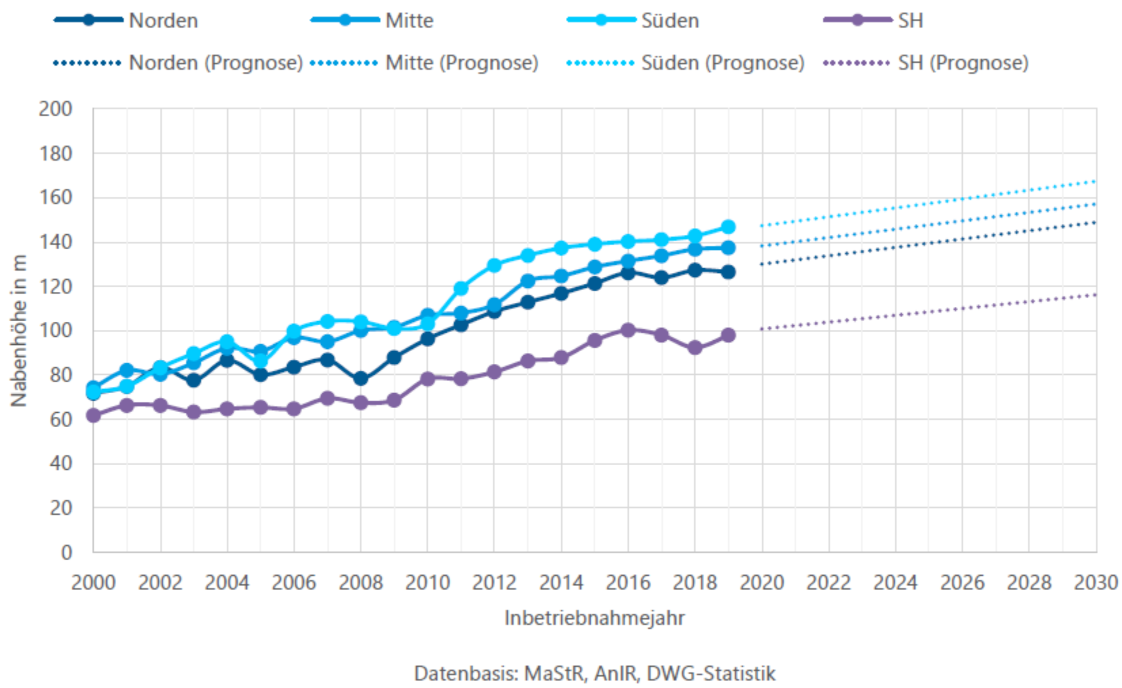

Figure 7: Development and forecast of mean hub hight (in m) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020

The specific nominal power represents the relationship between the nominal power of the turbine and the swept rotor area. The specific nominal power of the turbines has tended to decrease since 2012, which is due to the increasing rotor diameters (Figure 6). Systems with a lower specific nominal output, i.e. comparatively larger rotors, have more full-load-hours under the same wind conditions or achieve their nominal output at lower wind speeds and are therefore also referred to as low-wind systems. If two systems are compared with the same rotor diameter, the system with a higher absolute and therefore also specific nominal output is always more expensive and is therefore only suitable for comparatively higher wind speeds. Due to the prevailing conditions in RLP, low-wind turbines with a lower specific nominal output are more important in repowering than the increase in absolute turbine output. However, the value of the specific rated capacity in southern Germany is currently stagnating at approx. 270 W/m^2 as shown in Figure 8. Because the full-load-hours depend largely on the rated capacity and the wind speed in addition to technical influences, they are a useful indicator for calculating the expected electricity yield if there is no data on electricity yields from existing systems and only technical details and site conditions are available. The mean value of the full-load-hours of all wind turbines, e.g., for a federal state, can be used as a parameter to infer the future electricity yield from the installed rated capacity [32].

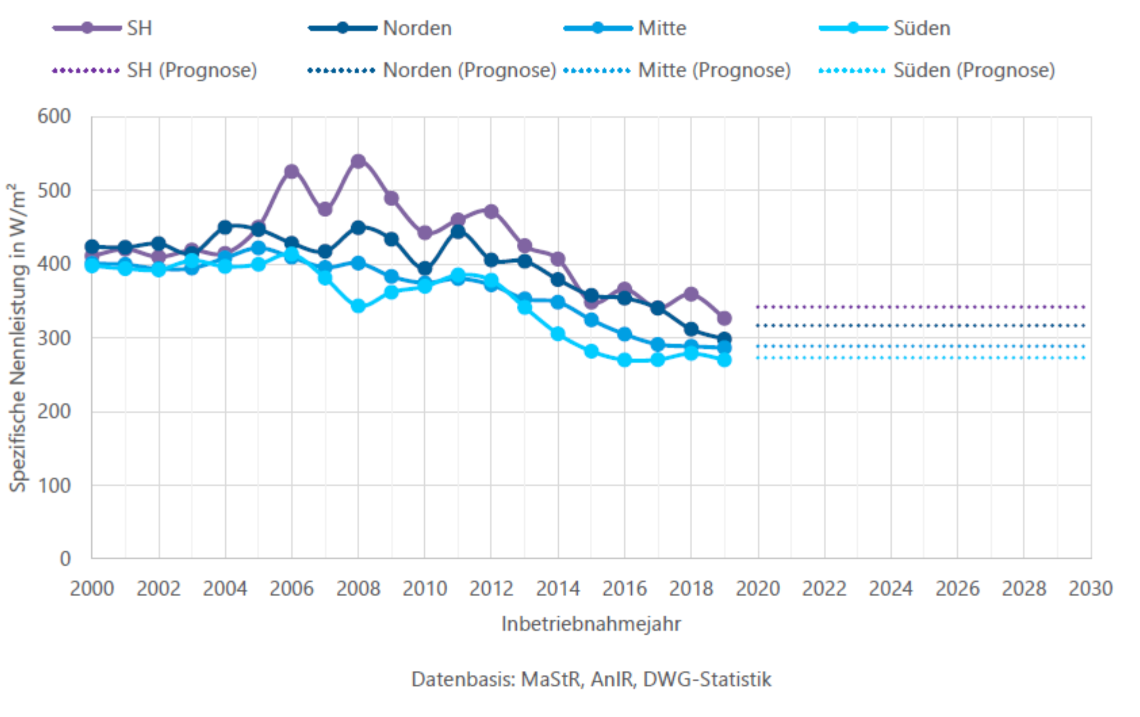

Figure 8: Development and forecast of the mean specific rated capacity (in W/m²) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020

Hence, the methodology of the DWG is adopted and applied in an own analysis of the electricity yield, the rated capacity and the full-load-hours as well as rotor diameter and hub height in RLP and the results are presented in section 4.1. This chapter continues with the explanation of the two main methods for the data analysis.

2.6 Regression analysis

2.7 Geospatial analysis

2.8 Résumé

The study of DWG shows how the technology of onshore wind turbines has continued to develop since 2000. A clear trend for an increase in the average rated capacity and the average rotor diameter of the newly commissioned systems can be seen. The mean total height of the turbines is also increasing, although this increase has been due to the increase in the mean rotor diameter for some years while the height of the lower blade tip remains the same. This also leads to an increase in the mean hub height. It is assumed that these trends will continue over the next ten years. A look at the configuration of the latest system models from different manufacturers supports this thesis (Enercon and Vestas, 2021). The development of offshore wind turbines suggests that even with a rotor diameter of 170 m and a nominal output of 6.6 MW no end of the system scaling is to be expected, where significantly larger systems are already available. However, the requirements regarding the construction are clearly different and the wind speeds at sea and thus the rotor diameter are of course not easy to transfer. –Source about other technical limitations- In order to calculate the electricity yield of future WTs in RLP, the following section analyses the master and movement data from 2019 for electricity yield, nominal output and full-load-hours. Additionally the area consumption of WTs in RLP is being assessed using the market master data register.

3 Materials and Methodology

3.1 Data

For the preparation and the analysis of the data, “R” which is a language and environment for statistical computing version 4.0.5 (2021-03-31) – “Shake and Throw” and RStudio Version 1.4.1106, which is the associated integrated development environment (IDE), is used [33]. Due to exhaustive code and iterative preparation steps the full documentation is not displayed here but can be found on `https://github.com/EliasCuadra/master-thesis-repowering` with explanatory README.md files that contain descriptions of variables and processing steps. Nonetheless, important aspects or code chunks are directly included or can be found in the appendix. Packages in use are: rio, data.table, tidyverse, magrittr, compare, leaflet, sp, raster, rgdal, htmltools, htmlwidgets, tmaptools, maptools, raster, sf, tmap, spatstat, rgeos and diagrammR. The data handling is mostly done with base R and deplyr from the tidyverse package collection. Deplyr is a grammar of data manipulation, providing a consistent set of verbs that help performing common data manipulation challenges [34]. The different sources of data are introduced subsequently.

3.1.1 Master and Movement data from Amprion

The so-called master and movement data from the transmission system operator amprion of the years 2012 to 2019 was available and used for analysis [26]. Despite the availability of older data sets in some cases only more recent years are used since it is assumed, that the usage of older data would, due to fast technical development, only distort the results in regards to future prediction. The original two data sets were already joined and prepared by the energy agency of RLP. The master data contains information about the location, commissioning and decommissioning date and the EEG system key of all EEG systems that were reported by the distribution network operator as part of the annual EEG report. The files also contain the systems connected directly or indirectly to the networks of the transmission system operator. Additionally, the transmission system operators are obliged to publish the so-called movement data that contains information about the quantity of electricity fed in and the amount of funded tariffs that have been payed [11]. The pre-processed data sets from the years 2015 to 2019 are stored within this project in data/amprion as EEG_StammBew_2015(- 2019)_Amprion-EAtlas.csv.

Further, The data from Amprion comes with 28 variables for the year 2019 of which only some are interesting for the analysis, some variable formats are not suitable and distorting data points are included. Thus, a preparation process must initially be carried out to clean and prepare the data. The kept variables are: community key, post code, place, rated capacity, commissioning date, system key and electricity yield. For the prediction of the electricity yield not all the WTs are meaningful and some outliers are removed from the data. On the one hand WTs with a rated capacity under 100 kW are considered too small for a reasonable assessment of new commercially operated systems. On the other hand some WTs are listed with a rated capacity up to 12 MW which might be because several WTs are registered as one. It is therefore assumed that a rated capacity larger than 4.5 MW does not reflect the average conditions, even though systems of this size exist. Also WTs that are built after February 15th each year are excluded since they have less time to generate electricity and therefore deliver misleading data. An interim result are five CSV files of the different years that only have relevant variables in the correct format and are free of outliers. As an insight the data from 2017 shows 1,623 WTs of which 101 are outliers, the data from 2018 shows 1,674 WTs of which 76 are outliers and the data from 2019 shows 1,702 WTs of which 46 are outliers. A plot that shows the total number of WTs from 2012 to 2019 is shown in Figure 9, which contains, as a foresight on the results section, a linear trend, that shows an estimated number of around 2,500 WTs in the year 2030. Only the data

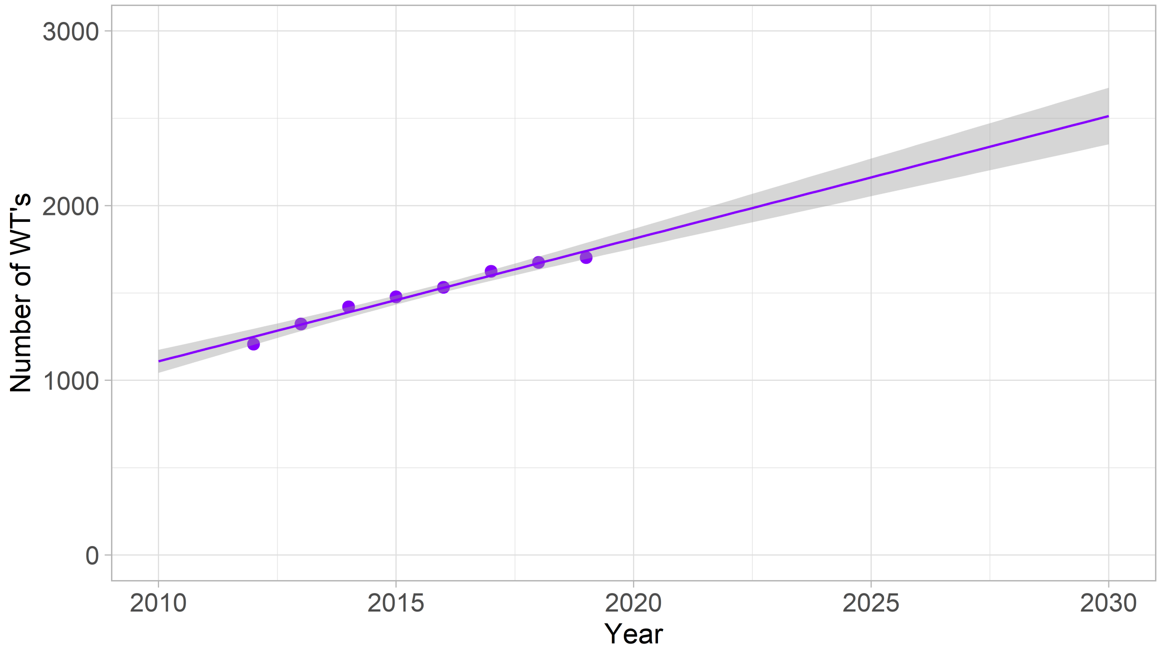

Figure 9: Number of total WTs in RLP from 2012 to 2019 according to transmission system operator Amprion

from 2019 is further processed and variables for the county and municipality names as well as the electricity yield in MWh and the full-load-hours, resulting from the division of electricity yield and rated capacity, are added. The data from 2019 is then divided in three files according to the commissioning date to find the WTs that are built either before 2005, before 2001 or between 2001 and 2005 and are therefore potentially suitable for a repowering process. A flow chart of the individual processing steps that have been performed is presented in Figure 10. The preparation was done to fulfill the main goal of analyzing the master and movement data regarding the electricity yield, rated capacity and the full-load-hours mainly in relation to the commissioning date. The full code can be seen in the Appendix A.1 as Code chunk 1. Amprion lists 1,702 WTs in RLP in 2019. In comparison to that, the Structure and Approval Directorate North registers 1,704 WTs with technical details and coordinate references that are connected to the public grid. This data set is not further used since it misses the EEG system key and can therefore not be joined with the other data sets.The other data set that is used is presented next.

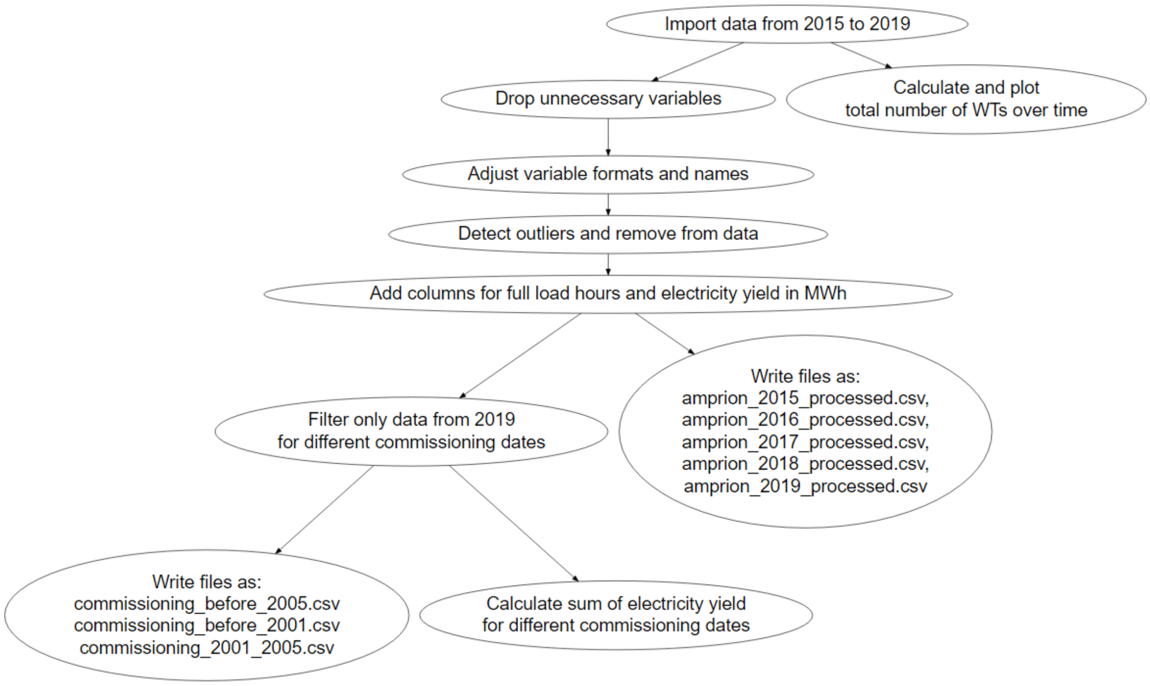

Figure 10: Flow chart of the proccessing steps

3.1.2 Data from the market master data register (MaStR - Marktstammdatenregister)

The MaStR contains data about all electricity and gas power generation units and can be freely accessed here: https://www.marktstammdatenregister.de/MaStR. The electricity units with the generation type “wind” for Rhineland-Palatinate that are in operation are extracted on the 23th of July 2021 as MaStR.csv and stored in this project in data/MaStR_amprion. This data set counts 1,752 WTs with 50 variables of which only 8 are kept: the rated capacity, the commissioning date, the community key, the coordinates (CRS: WGS84), hub height, rotor diameter and EEG system key. It does not contain the amount of electricity fed into the public grid. Thus, to calculate the electricity generation per area the data of the MaStR and amprion needs to be joined together according to the EEG system key. The process of preparing the MaStR data and joining it with the data from amprion of 2019 is shown as a flow chart in Figure 11. The R code is stored as MaStR_amprion.R in the MaStR_amprion folder and can be seen in the Appendix as XXX. The result are 1,620 WTs that could be correctly assigned and are ready for further analysis and stored as MaStR_amprion2019.csv in the same source location. The analysis methods are presented in the two following subsections.

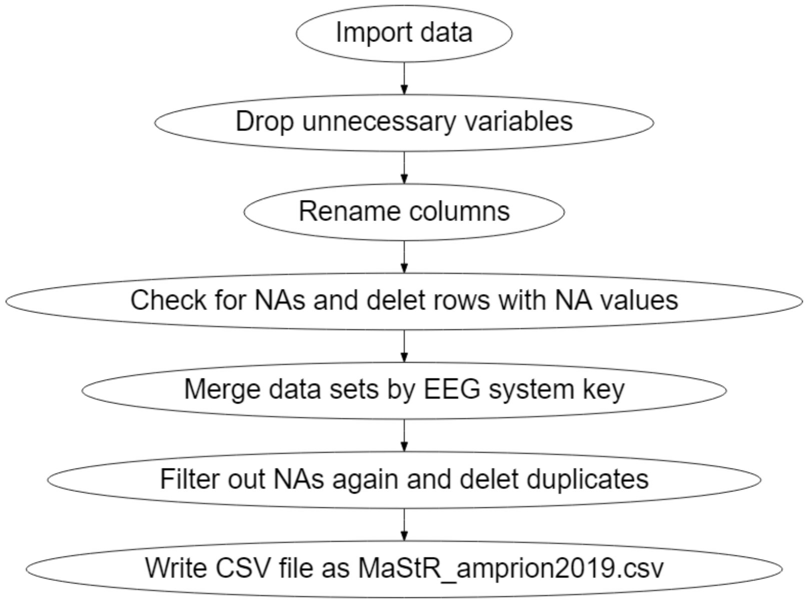

Figure 11: Flow chart of merging process

3.2 Methods

3.2.1 Regression analysis

After the preparation, the data is firstly analyzed regarding the amount of electricity generated per WT and per year. For this purpose, a linear and a 3rd order polynomial regression, which allow for a forecast until 2030, is carried out. The amount of electricity fed in, here referred to as the electricity yield, is the dependent variable and the commissioning date as the independent variable. Secondly the electricity yield is plotted over the rated capacity and henceforth only linear trends are applied to generate more conservative and appropriate estimation of the future values. For the next analysis a plot of the rated capacity over the commissioning date is generated. For this only data from 2019 is used since the rated capacity of the already installed WTs do not change over time. Further the full-load-hours as a concept of the degree of utilization is analyzed in regard to the WTs commissioning date. The degree of utilization might be more dependent on the wind conditions than the technical development and is therefore specifically good for predictions and therefore data from the past 5 years is analyzed. In addition to the wind conditions the full-load-hours depend on the specific nominal output, which means the rotor diameter, and hence the technological development cannot be disregarded. This means that old data might still deliver a wrong impression on future predictions but also might account for weaker years in terms of wind conditions since 2019 might be a stronger wind year.

Since it is crucial not only to know the electricity yield per WT but also the electricity yield per area to estimate how much of the area of Rhineland-Palatinate must actually be covered with WTs in order to achieve the target of 22 TWh of wind energy per year in 2030. Therefore data from the master data register that contains geographic information about the WTs is used to calculate their area consumption and that process is described in the next section.

3.2.2 Geospatial analysis

4 Results

4.1 Electricity yield, rated capacity and full-load-hours in Rhineland-Palatinate

The diagnostics of the electricity yield show in all linear and polynomial models the same characteristics. Even if they slightly differ from each other and the model assumptions might not be 100 % optimal for regression analysis they are also not fundamentally violated. In Appendix YYY the diagnostic plots of the electricity yield over the commissioning date from the year 2019 are shown as an example. The residual vs fitted values plot show that the residuals become greater with increasing value for the electricity yield. This makes sense since the rated capacity for WTs increases and therefore changes the magnitudes of electricity generation over time. The normal QQ plot shows that the residuals of average values are normally distributed but as the values become great or small there is clear deviation from a normal distribution. This might be due to the non-linear development of the WT technology. The scale location plots reveal that the residuals are more or less spread equally among the range of predictors with slightly increasing variance with increasing values, which must be like this since this was already indicated in the residuals vs fitted values plot. The residuals vs leverage plot shows that none of the observations is without Cook's distance and therefore there is no influential outlier.

All models are highly significant with p-values less than 0.001 and the linear models have R^2 values of 0.68 - 0.70, which means that around 70 % of the variation in the electricity yield can be explained by the commissioning date. By using a 3rd order polynomial formula the value for R^2 increases to up to 73 %. This value could not significantly be increased by using a higher order. This means that the fit of the model can be slightly improved using the polynomial model but it might lose prediction power due to the bias variance trade-off. Intuitively an infinitely or exponentially growing electricity yield is of course not realistic from a physical or technical point of view. Therefore, the prediction of the polynomial models of more than 15,000 MWh per WT on average in the year 2030 seems too high and the assumption of 10,000 MWh per WT of the linear trends is more reasonable. However, the DWG forecast in Figure 5 shows a disproportionate increase in the average nominal power, which in turn means that at locations with optimal wind conditions and rapidly advancing technology, disproportionate growth in electricity yield per WT is possible. Nonetheless, only a few locations have optimal conditions and a more conservative estimation is chosen in this context, which might be different in the assessment of single sites. The plot of the data and all trends are shown in Figure 12. For the given reason the average electricity yield of the three linear trends in 2021, which amounts to 7,400 MWh per WT, together with the upcoming results from the rated capacity and full-load-hours is used for further calculations. For the following plots and trends the diagnostics and significance is

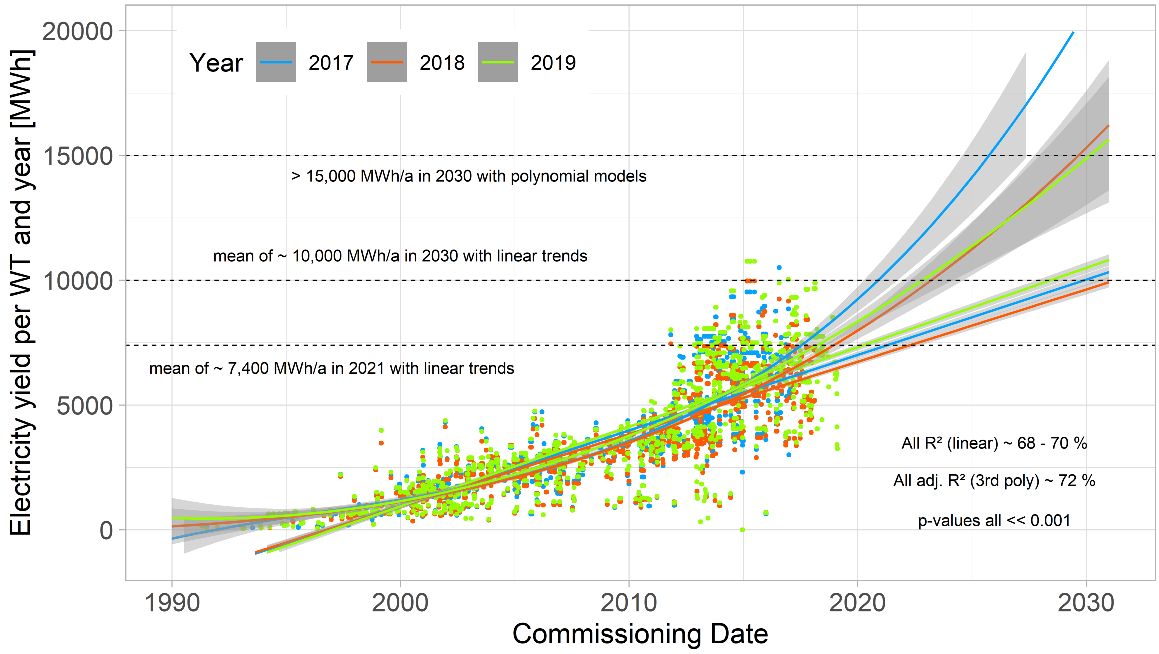

Figure 12: Development and forecast of electricity yield in Rhineland-Palatinate using data from 2017 to 2019 and a linear an polynomial model

not further discussed since there is no sign of abnormalities apart from the patterns that occur due to the steps in which the rated capacity of generators increase and the assumed non-linear technological development. The plot of the electricity over the rated capacity is shown in Figure 13.

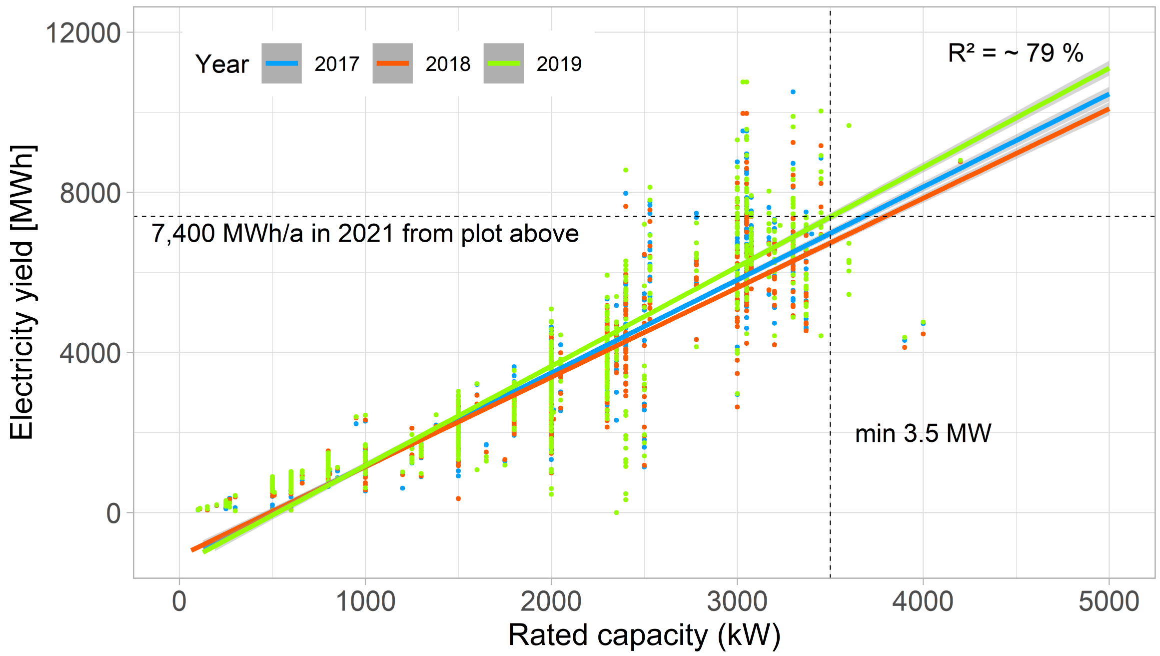

Figure 13: Electricity yield over rated capacity in RLP with data from 2017 to 2019

As expected the electricity yield increases with increasing rated capacity and therefore also more recent commissioning date because the size and generator technology has continued to advance. But since the year 2017 suggests a steeper increase over the year 2018 this is not the only reason and the annual wind conditions might influence this trend significantly. But not only the overall electricity yield increases also the variance increase. This is also logical since the different and fluctuating wind conditions lead to a greater magnitude of difference in electricity yield when using a larger generator. It can also be seen that the rated capacity clusters around certain values which is due to the availability and performance of specific generator series. Common sizes are 2, 3 or 3.7 MW but are also available in between. To generate the average electricity of 7,400 MWh/a that were presented before, as a minimum, turbines with and average capacity of 3.5 MW must be used. The plot of the rated capacity over the commissioning date with data from 2019 is shown in Figure 14. It displays again the characteristic pattern of specific rated capacity values and the mean of 3,500 kW installed power in 2021 per WT as well as a prediction for the year 2030 with 4,500 kW using a linear trend. Similarly the study of the DWG shows a predicted rated capacity of around 3.5 MW in 2021 and an even higher rated capacity of around 5.5 MW in 2030. Hence, this 3.5 MW are used for further calculations. The next plot shows the full-load-hours over the commissioning date in Figure 15. The linear trends for the year 2015 until 2019 have more or less the same slope and are not deviating strongly. This indicates relatively stable conditions. It also seems that the more recent the data the higher the estimates, which could be

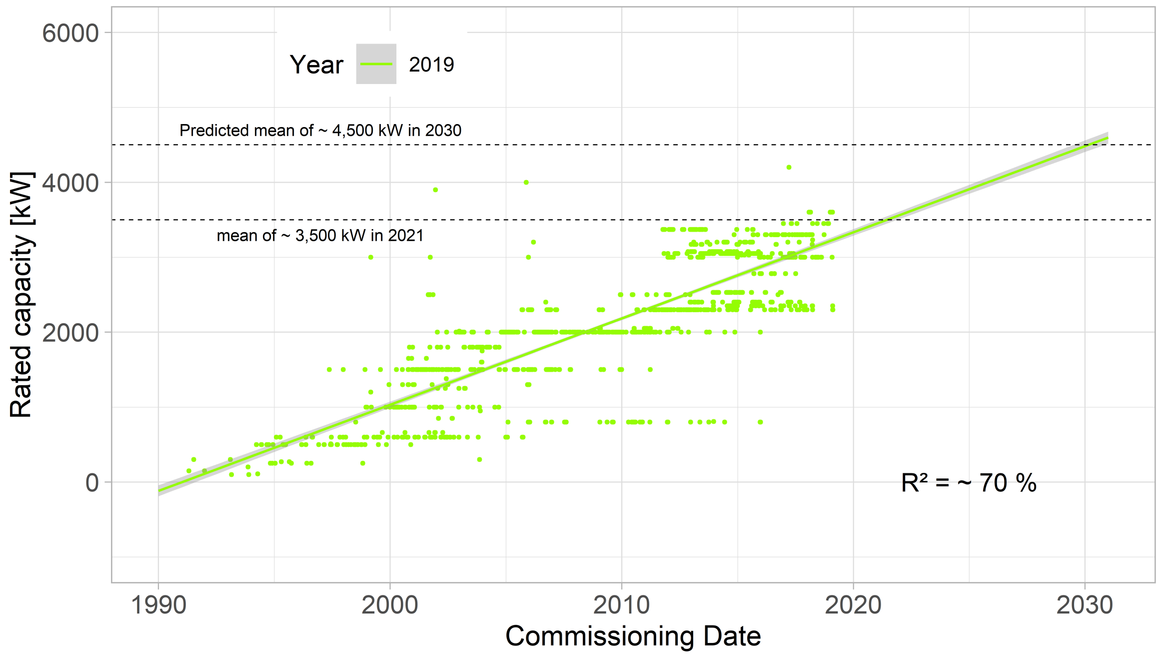

Figure 14: Rated capacity over commissioning date

explained through increasing technology especially again the increasing rotor diameter and therefore the reduced specific nominal power is decisive. On the contrary the estimation of the data from 2015 is among the highest, even though the latest technology is not reflected here. The year 2017 also has higher full-load-hours than the year 2018. This nicely reflects the fluctuation in wind conditions and means that the years 2015 and 2017 might be better wind years than the years 2016 and 2018. The mean of all models for 2021 is around 2,300 h/a and is therefore used for further calculation. The prediction for 2030 is around 2,800 h/a on average. If this is compared to the study of the DWG it can be seen that the DWG similarly shows average full-load-hours for the south of Germany in 2000 of around 1,300 and in 2016 of around 2,000 and the prediction for 2021 lies equally at around 2,300 h. The estimation for 2030 of the study of DWG shows a lower value of less than 2,500 h. This might be because the study of the DWG uses more data from different sources, probably a more sophisticated model and also the prediction is done for the whole of southern Germany. But it seems as to calculate with the value of 2,300 full-load-hours does definitely not lead to an overestimation. Divided by the total number of hours per year that equals to a load factor of around 26 %, which is much more than the mentioned 19 % from the literature [27] from 2009. This can, again, be well explained through the increasing rotor and decreasing specific nominal power which leads to a better utilization of weak winds. Lastly if we multiply the estimated full-load-hours by the average rated capacity for 2021 the result is 8,050 MWh/a, which is higher than the linear trends suggest. This is because the development of the rated capacity and the rotor diameter are actually not completely captured by a linear relationship. If compared to the polynomial models with estimations for the year 2021 of around 8,000 - 10,000 MWh/a this result seems more similar. If we assume an average electricity generation of 7,400 MWh/a the number of WTs needed to generate the demanded 20 TWh is around 2,700 WTs, if on average 8,050 MWh/a could be harvested then this would require around 2,484 WTs. It seems that if the average growth of the total number of WTs in RLP continues as predicted initially the goal of around 2,500 WTs in RLP is realistic. Of course, WTs with lower total electricity yield would have to be repowered additionally but it shows that it is not totally out of the scope. On the contrary, due to legal reasons and resistance from the citizens, the increase was slowed down sharply from 92 newly commissioned WTs in 2017 to 27 newly commissioned WTs in 2019 [26]. Experts from the wind industry particularly criticize the difficult approval procedures. The biggest mistake of the federal government was to introduce an "obligation to tender" for new wind turbines [35].

In the end of this section it is to mention that this increasing development should not be misunderstood that the overall electricity yield of an area can be increased in the same way. Larger WTs have to be spaced further apart, so even though they might have a higher electricity yield, the overall electricity yield per area might not increase as much as expected. Although there might be strong economic reasons to build greater WTs and also to harvest higher wind speeds at greater altitudes, the overall energy extraction per area has certain limits that cannot be exceeded. The calculations of the respective area consumption are presented in subsections XV.

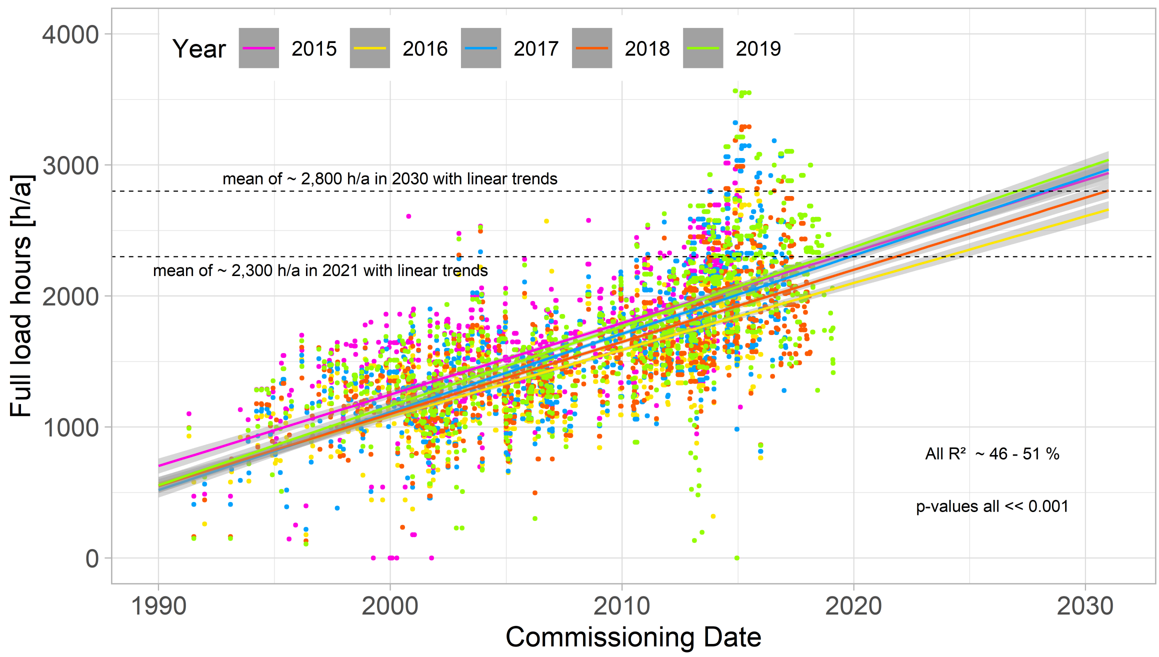

Figure 15: full-load-hours over the commissioning date using data from 2015 - 2019

4.2 Repowering potential

The WTs in RLP that are potentially suitable for repowering within the next 10 years are older systems which have been divided into two categories (Table 21): commissioned before 2001 and between 2001 and 2005. The electricity yield would be more than 7 times greater if all systems with a commissioning date before 2001 would be repowered and around 3.7 times as much as if additionally all systems with a commissioning date between 2001 and 2005 are repowered. These values are theoretical and represent a repowering rate of 100%. This means a total replacement of 514 WTs with accordingly larger area consumption. It is also highly questionable if all of the old systems can be replaced due to distance regulations and approval procedures. In this context repowering is a misleading term since it suggests that a system is technically enhanced, but in this case it means the deconstruction of old systems and new building of another system, which might even be in a different location. This is also why the the approval procedures and distance regulations and also measures to protect the environment are not different as in the case of first construction of a WT. Thus, for a technical assessment of the wind energy potential in RLP, the respective electricity yield per WT and especially per area is determining. Whether and how WTs are repowered is then once the potential is assessed an economic and legal consideration. Hence, the calculation of the area consumption follows next.

Commission	Number of WTs	Electricity yield [GWh]	Potential [GWh]	Increase [%]
before 2001	186	186	1376	740
2001 to 2005	328	655	2427	371

Table 2: Repowering potential based on the 100 percent replacement of wind turbines commissioned either before 2001 or from 2001 to 2005.

4.3 Rotor diameter, hub height and area consumption

After taking WTs out of the data that would distort the results 1195 WTs remained for analysis. The distortion w It is to mention that almost 400 WTs had to be taken out of the data set and also the R^2-value is not very high, thus the overall prediction power of the model might be low.

Nonetheless, the average distance to the nearest WT of all WTs is a reasonable 417 m which equals to an area consumption per WT of about 174,168 m^2 or 0.174 km^2. This means that the total area covered with currently 1702 WTs is about 296.4 km^2, this equals to around 1.5 % instead of the 1.9 % that were theoretically derived in chapter 2.1 of the total area of RLP which is 19,847 km^2. With an electricity yield of 6.782 TWh in 2019 this means that the average electricity yield per area and year equals to around 22.88 kWh/m^2a which is a constant power output of about 2.61 W/m^2. This exceeds the value of 2.2 W/m^2 if compared to the literature value from 2009 with an assumed average wind speed of 6 m/s that was introduced in chapter 2.1 and calculated in formula 4 and 6. The actual average wind speed must be 6.3 m/s to reach a power output of about 2.61 W/m^2. Hence, this is definitely an indicator for the utilization of higher wind speeds in greater altitude with the technical development towards greater hub heights. The increase in rotor diameter cannot explain this development if the WTs have to be spaced further apart as seen in formula 6. The average distance to the next WT in relation to the rotor diameter is 4.9 which is relatively close to the five times the rotor diameter mentioned earlier and in the literature [27].

The plot that shows the electricity yield per m^2 and year over the commissioning date of the whole joined data set that originated from the MaStR and the master and movement data from amprion of 2019 is show in Figure 16. Although the model is highly significant only 11 % of the variation in the depended variable is explained by the commissioning date. Therefore it is not clear if this model is enough to make clear predictions. Due to the constant technical development it makes sense to take

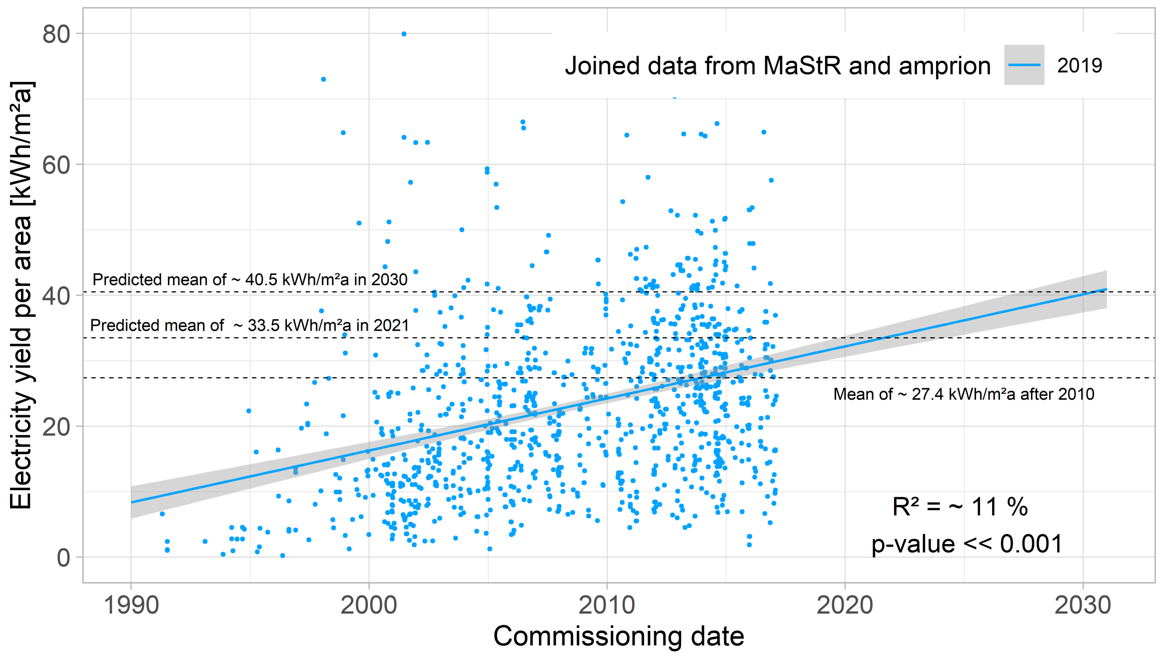

Figure 16: Electricity yield per m² and year over the commissioning date

more recent years for future predictions. Thus, only the results of the WTs with a commissioning date after 2010 are used for further analysis. The distance to the nearest neighboring WT increases then up to 474 m, but decreases in relation to the rotor diameter to 4.7 times the diameter. This might be due to increasing rotor diameter but limited space. This leads to an interesting trade-off between greater and more efficient WTs and the occurring shadowing effect that reduces the efficiency of a wind park.

The average area consumption of a WT built after 2010 is around 243,285 m^2 which is 0.243 km^2. The average electricity yield is about 27.4 kWh/m^2 which relates to a constant power output of 3.1 W/m^2. Hence, the electricity yield per area is increasing over time and the reduced distance between WTs in relation to their rotor diameter and with it possible shadowing effects are surpassed by the effect of utilizing greater wind speeds at higher altitudes. If the increase in efficiency can be kept with increasing rotor diameter and a reduced or similar area consumption, the rotor diameter has indeed again a big impact on the overall electricity yield. This trade-off between the possibility of energy extraction with rotors and the respective demand in space should therefore be examined in further studies, that an exact threshold of this trade off can be defined.

According to Figure 16 three possible scenarios using the mean of WTs with a commissioning date after 2010 and values of the linear trend for 2021 and 2030 are introduced in table 3 for the calculation of a future area consumption with an electricity demand of 22 TWh per year. It remains unclear, if a constant power output of 4.6 W/m^2 predicted for 2030 with a required average wind speed of 7.62 m/s, as presented as the third scenario, is reasonable for RLP. Although, it seems possible regarding the literature values of 1 to 7 W/m^2 mentioned by Linow [31], if compared with the occurrence of this wind speed shown in Figure 2 at 140 m above ground, it seems rather unlikely. Nevertheless, despite some problems regarding regulations and approval processes it is definitely clear that the average hub height is steadily increasing and to be expected above the mentioned 140 m (Figure 7). ***own calculations***. Nevertheless it becomes clear that even in this best case Scenario 2.7 % of the area of RLP has to be covered with WTs which is 1.8 times as much as today, if a scenario with the average predicted electricity yield of 33.5 kWh/m^2 is true then 2.2 times the current area need to be covered and finally if the electricity yield per area cannot significantly increased over time the area that has to be covered with WTs to generate a demand of 22 TWh in 2030 is around 4 % which is 2.7 times the area that is currently covered with WTs. Additionally after the year 2030 a further increase in electricity demands through electrification is expected and covering more than 4 % of the area with WTs will of course also increase people's concerns and resistance. Therefore, it is still questionable if the state of RLP will succeed in fulfilling their goals on supplying two thirds of their electricity demand from own wind power. Nonetheless, this work showed that the potential is certainly given.

Scenario	Electricity yield per area [kWh/m²a]	Power output per area [W/m²]	Area Consumption [km²]	Share of the area of RLP [%]	req. av. wind speed [m/s]
mean > 2010	**27.4**	**3.1**	**802.3**	**4**	**6.7**
mean 2021	**33.5**	**3.8**	**656.7**	**3.3**	**7.17**
mean 2030	**40.5**	**4.6**	**543.2**	**2.7**	**7.63**

Table 3: Three scenarios of electricity yield per area and year and their respective area consumption and required wind speed if an electricity of 22 TWh should be generated with WTs in 2030

5 Discussion

6 Conclusion

- Give a short summary of what has been done and what has been found.
- Expose results concisely.
- Draw conclusions about the problem studied. What are the implications of your findings?
- Point out some limitations of study (assist reader in judging validity of findings).
- Suggest issues for future research.

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A Appendix

A.1 Code chunk 1

```
#######################################################################
#Preparation of the master and movement data of the transmission system#
#operator Amprion from 2015 - 2019                                    #
#######################################################################

#packages
Sys.setenv(LANG = "en")
pacman::p_load(rio, data.table, tidyverse, tidyr, purrr, magrittr, compare,
               ggplot2, DiagrammeR)

#Import data and format columns
amprion_2015 <- read.csv("EEG_StammBew_2015_Amprion-EAtlas.csv")
amprion_2016 <- read.csv("EEG_StammBew_2016_Amprion-EAtlas.csv")
amprion_2017 <- read.csv("EEG_StammBew_2017_Amprion-EAtlas.csv")
amprion_2018 <- read.csv("EEG_StammBew_2018_Amprion-EAtlas.csv")
amprion_2019 <- read.csv("EEG-StammBew_2019_Amprion-EAtlas.csv")
names(amprion_2019)[1] <- "gem"
names(amprion_2018)[1] <- "gem"
names(amprion_2017)[1] <- "gem"

#calculate and plot trend of total WT's
year <- c(2012:2019)
wts <- c(1207, 1322, 1420, 1478, 1532, 1624, 1675, 1702)
year_wts <- data.frame(year, wts)

lm_year_wts <- lm(year_wts$wts ~ year_wts$year)
summary(lm_year_wts)



pyear_wts <- ggplot() +
```

```
  geom_point(data = year_wts,
             aes(x= year, y=wts),
             size = 2, colour = "#8600fd") +
  geom_smooth(data = year_wts,
              aes(x=year, y=wts),
              method=lm, se=TRUE, fullrange = TRUE,
              size = 0.5, colour = "#8600fd")  +
  theme_light() +
  ylim(0, 3000) +
  xlim(2010, 2030) +
  xlab("Year") +
  ylab("Number of WT's") +
  theme( axis.text=element_text(size=11),
         axis.title=element_text(size=12),
         plot.title = element_text(size=14),
         legend.position = c(0.85, 0.9),
         legend.direction = "horizontal")


#print plot
pyear_wts + theme(legend.position = c(0.25,0.9))



#save plot
ggsave("results_of_analysis/year_wts.png",
       plot = last_plot(),
       dpi = 900,
       width = 7,
       height = 4)

#Variable selection
selection_2015 <- amprion_2015[,c(1:3,8,10,17,27)]
selection_2016 <- amprion_2016[,c(1:3,8,10,17,27)]
```

```r
selection_2017 <- amprion_2017[,c(1:3,8,10,17,27)]
selection_2018 <- amprion_2018[,c(1:3,8,10,17,27)]
selection_2019 <- amprion_2019[,c(1:3,7,9,16,26)]

#formatting commissioning date
selection_2015$inbetriebnahme <- as.Date(selection_2015$inbetriebnahme,
                                         "%d/%m/%Y")
selection_2016$inbetriebnahme <- as.Date(selection_2016$inbetriebnahme,
                                         "%d/%m/%Y")
selection_2017$inbetriebnahme <- as.Date(selection_2017$inbetriebnahme,
                                         "%d/%m/%Y")
selection_2018$inbetriebnahme <- as.Date(selection_2018$inbetriebnahme,
                                         "%d/%m/%Y")
selection_2019$inbetriebnahme <- as.Date(selection_2019$inbetriebnahme,
                                         "%d/%m/%Y")

#find outliers
outliers_2015 <- filter(selection_2015, leistung < 100 | leistung > 4500 |
                          inbetriebnahme > "2015-02-15")
outliers_2016 <- filter(selection_2016, leistung < 100 | leistung > 4500 |
                          inbetriebnahme > "2016-02-15")
outliers_2017 <- filter(selection_2017, leistung < 100 | leistung > 4500 |
                          inbetriebnahme > "2017-02-15")
outliers_2018 <- filter(selection_2018, leistung < 100 | leistung > 4500 |
                          inbetriebnahme > "2018-02-15")
outliers_2019 <- filter(selection_2019, leistung < 100 | leistung > 4500 |
                          inbetriebnahme > "2019-02-15")

#create df without outliers
selection_2015_without_outliers <- setdiff(selection_2015, outliers_2015)
selection_2016_without_outliers <- setdiff(selection_2016, outliers_2016)
selection_2017_without_outliers <- setdiff(selection_2017, outliers_2017)
selection_2018_without_outliers <- setdiff(selection_2018, outliers_2018)
```

```r
selection_2019_without_outliers <- setdiff(selection_2019, outliers_2019)

#delete some
rm(selection_2015, selection_2016, selection_2017, selection_2018,
   selection_2019)

#add electricity yiel in MWh and full load hours
selection_2015_without_outliers <- selection_2015_without_outliers %>%
  mutate(flh = menge_kwh/leistung) %>%
  mutate(menge_mwh = round(menge_kwh/1000))
selection_2016_without_outliers <- selection_2016_without_outliers %>%
  mutate(flh = menge_kwh/leistung) %>%
  mutate(menge_mwh = round(menge_kwh/1000))
selection_2017_without_outliers <- selection_2017_without_outliers %>%
  mutate(flh = menge_kwh/leistung) %>%
  mutate(menge_mwh = round(menge_kwh/1000))
selection_2018_without_outliers <- selection_2018_without_outliers %>%
  mutate(flh = menge_kwh/leistung) %>%
  mutate(menge_mwh = round(menge_kwh/1000))
selection_2019_without_outliers <- selection_2019_without_outliers %>%
  mutate(flh = menge_kwh/leistung) %>%
  mutate(menge_mwh = round(menge_kwh/1000))

#write files
write.csv(
  selection_2015_without_outliers,
  "results_of_preparation/amprion_2015_processed.csv")
write.csv(
  selection_2016_without_outliers,
  "results_of_preparation/amprion_2016_processed.csv")
write.csv(
  selection_2017_without_outliers,
  "results_of_preparation/amprion_2017_processed.csv")
```

```r
write.csv(
  selection_2018_without_outliers,
  "results_of_preparation/amprion_2018_processed.csv")
write.csv(
  selection_2019_without_outliers,
  "results_of_preparation/amprion_2019_processed.csv")

#find different commissioning dates
commissioning_before2001 <- subset(selection_2019_without_outliers,
                                   inbetriebnahme < "2000-12-31")
sum(commissioning_before2001$menge_mwh)
commissioning_before2005 <- subset(selection_2019_without_outliers,
                                   inbetriebnahme < "2005-12-31")
commissioning_2001_2005 <- subset(commissioning_before2005,
                                  inbetriebnahme > "2000-12-31")
sum(commissioning_2001_2005$menge_mwh)

#write csv
write.csv(commissioning_before2001,
          "results_of_preparation/commissioning_before_2001.csv")
write.csv(commissioning_2001_2005,
          "results_of_preparation/commissioning_2001_2005.csv")
write.csv(commissioning_before2005,
          "results_of_preparation/commissioning_before_2005.csv")
```

Declaration of Authorship

I hereby confirm that I have authored this Master's Thesis independently and without use of others than the indicated sources. All passages which are literally or in general matter taken out of publications or other sources are marked as such.

Berlin, August 20, 2021

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Elias Cuadra Braatz