Windenergy 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

CPI	Consumer Price Index	ETF	Equity Traded Funds
ETH	Eat the Horse	XLM	Xetra Liquidity

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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 [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 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. When developing municipal climate protection, a sound strategy is required regarding the legally anchored striving for climate neutrality of the state of RLP [4]. Even more pressure comes from the recent press release No. 31/2021 of April 29 in 2021 [5], in which the first Senate of the Federal Constitutional Court decided that the regulations of the Climate Protection Act of December 12 in 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 onwards. 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]. This shows that this study is highly embedded in a socio-economic context. The energy transition is a cornerstone of a decent strategy to climate neutrality and RLP wants to play a pioneering role in the implementation of the energy transition. The state government publishes on its website that RLP will cover 100 % of its electricity needs from renewable energies by 2030 [8]. 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. The study area and the modeled wind speeds taken from the Windatlas RLP [9] are seen in figure 1.

The gross electricity generation in RLP from wind power rose in 2017 with 5.9 TWh to 29 % of the total 20.7 TWh generated electricity. The total consumption in the same year was 29.1 TWh [10]. 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. Various scenarios about future electricity consumption assume a slightly reduced to increased, but on average relatively unchanged electricity consumption for the whole of Germany in 2030 [11]. In order to achieve the self-set goals of using two thirds of the electricity demand from wind power with constant or higher electricity demand, electricity generation with wind turbines (WT's) must be increased to at least 14 TWh per year. If RLP wants to become independent of electricity imports, an increase to around 20 TWh is necessary. There are two ways of increasing the amount of electricity generated by wind energy. On the one hand, areas that are still available can be identified and built on with new WPP's. On the other hand, existing old systems, whose absolute electricity feed-in quantity is low, can be replaced by new, higher and more efficient systems through the so-called "repowering." The aim of this work is to develop a methodology for calculating the wind energy potential and its related area consumption at the state level as well as for the districts and association communities in RLP. With this results an evaluation of the desired expansion targets should be assessed. The central three questions of this work are therefore:

1. How much electric energy can be generated by a new wind turbine from 2021 until 2030 in RLP per area?

2. How large is the potential when all wind turbines with a commissioning date before 2005 are repowered?

3. How much area is needed to generate the target amount of 20 TWh out of wind energy?

In order to answer these questions, the technical fundamentals of the electricity yield from WT's are explained first. Subsequently, the master and movement data provided by the transmission system operator Amprion, which contains all electricity fed into the public grid by WT's and other technical information, is analyzed and forecasted up to the year 2030. The respective area consumption to generate that electricity is calculated using a GIS based approach and data from the market master data register (MaStR). As a by-product the greenhouse gas reduction potential can be derived from the potential for electricity generation. Knowing the electricity potential per area, the required area for the generation targets can be calculated and an assessment of the given expectations can be made subsequently.

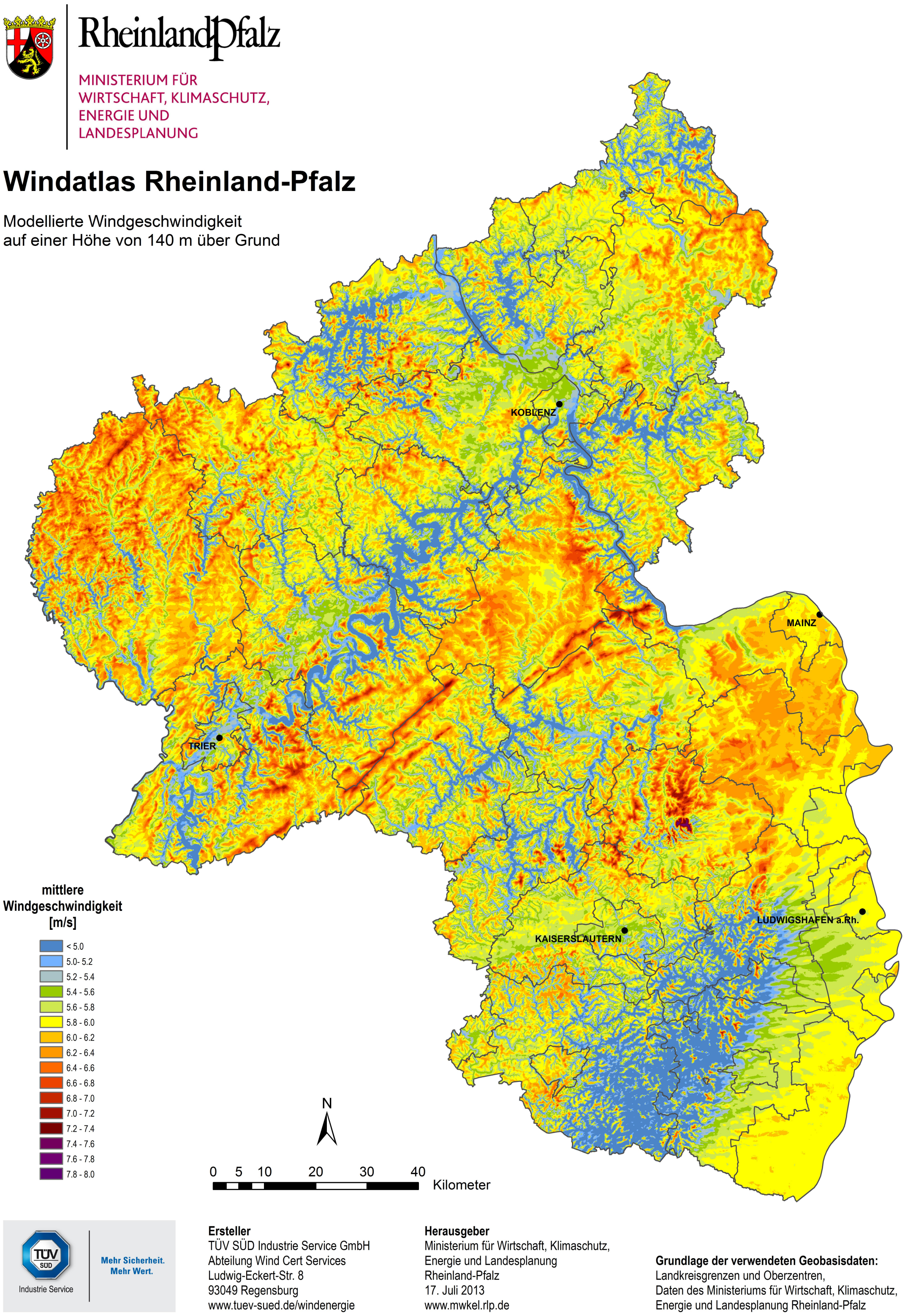

Figure 1: Wind speeds in RLP 140 m above Ground [9].

2 State of the art

2.1 Physical basics

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 [12]. A wind turbine usually consists of the three main components; rotor blades, nacelle and tower. Besides other elements the nacelle contains; the gearbox, the generator, the transformer and the control system [13]. The mostly three rotor blades 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. Mainly the gearbox and the generator convert 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 [14].

The transmission system operators, in this case Amprion, are obliged to publish so-called master and movement data for each calendar year in accordance with section 77 Renewable Energy Act 2017 [15]. These movement data include the annual electricity generation and the system key. The movement data for RLP are 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. approx. 6.782 TWh [16].

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]:

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

The air throughput or 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 with[2]:

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

[1] $E_{kin} = kinetic\ energy,\ m = mass\ of\ air,\ v = wind\ speed$
[2] $\rho = density\ of\ air,\ A = rotor\ area$

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 [17] and BWE [18])

In Formula 3 it becomes clear that the wind speed is the decisive factor for the performance of a WT. Because WT's are build to perform at lower wind speeds most of the time they can not operate at very high wind speeds an 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 2. If the density of air is 1.3 kg per m³ and there is an average windspeed of 6 m/s, which could be realistic for many sites in RLP in 140 m above ground, as seen in figure 1, then the typical power of the wind per square meter hoop is:

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

The curve of power per m^2 in relation to the wind speed is also shown in figure 2. Of course, not all

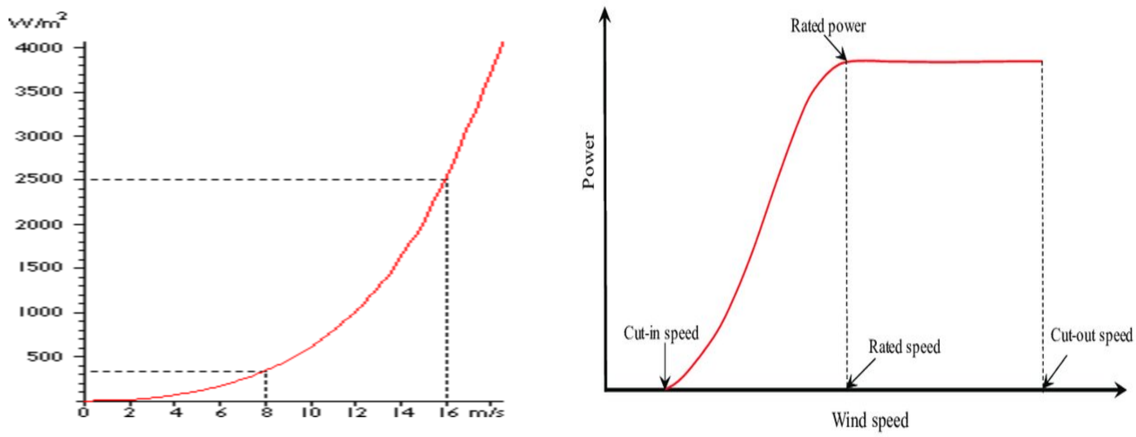

Figure 2: Left: Power of the wind per area over wind speed; Right: Typical load profile of a WT

the wind's power can be converted and there are further losses when converting kinetic energy into electrical energy in the generator. The efficiency using the winds energy in theory after Alber Betz is a maximum of 59 % also called the Betz limit [19], but in practice it is often around 40 % to a maximum of 50 % [20]. If the average rotor diameter installed in RLP in 2020 was 130 m (figure 3)

[3] $r = radius\ of\ rotor$

with an efficiency of 50 %, then the average power of one WT is:

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

The amount of energy also increases proportionally with increasing rotor diameter. This explains why the rotor diameters become larger in practice (figure 3). But WT's with larger rotors have to be spaced further appart. In the literature values from 3 to 8 times the rotor diameter depending on the main direction of the wind can be found [17]. If we assume further that windmills in RLP are spaced on average 5 times their diameter apart from each other, from equation 5 follows that the energy per area land mass is:

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

This means that independently of the rotor size, there is a limit of around 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 mass depending on the site conditions [21]. Nonetheless, building higher WT's 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 thus increase the power of the wind by 30 % and therefore the hub heights also tend to increase (figure 4). The actual way that wind speed increases with heigth 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 WT's are design to start operating at wind speeds 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 can be called the "load factor" and a typical load factor in Germany is around 19 %, 22 % in the Netherlands and 30 % in the United Kingdom [17]. Lastly it can be estimated how much area is needed when we assume a rounded and constant electricity yield of 2 W/m^2 and an electricity demand of 20 TWh per year in RLP:

$$A_{20TWh} = \frac{20 * 10^{12} Wh}{2W/m^2 * 8760h * 10^6} = 1141.5km^2 \tag{7}$$

The total area of RLP is 19,847 km^2, which means that the desired amount of electricity coming from wind energy would be equivalent with covering roughly 5.8 % of the area with WT's. The actual 6.7 TWh of electrical energy generated in RLP would demand 382.4 km^2 which equals to about 1.9 % of the area of RLP. If the same calculation for the hole of germany is done the demanded 600 TWh would need an area of about 34,246 km^2 which is rounded 9.5 % of the area. Whereas the area consumption for RLP is still somehow imaginable it is clear that covering nearly 10 % of Germany with WT's is very uncertain. It should also be noted, that the assumption of an average wind speed of 6 m/s could be an overestimate and the area consumption becomes greater. In chapter 3 the actual numbers for RLP are presented and therefore allow for an evaluation of this theoretical approximation.

For further explanation to 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 [22], is used as a guide and its results are presented in the next subsection.

2.2 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). RLP is part of the southern region. The development of the rotor diameter and hub hight is shown in figure 3 and 4. The study of DWG suggests that the wind energy potential, i.e. the theoretical electricity yield of a wind turbine for future systems, can and will be calculated in this work 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. The **full load hours** are formed from the quotient of the annual electricity yield and the rated capacity and are an indicator of the degree of utilization of a wind turbine like the load factor.

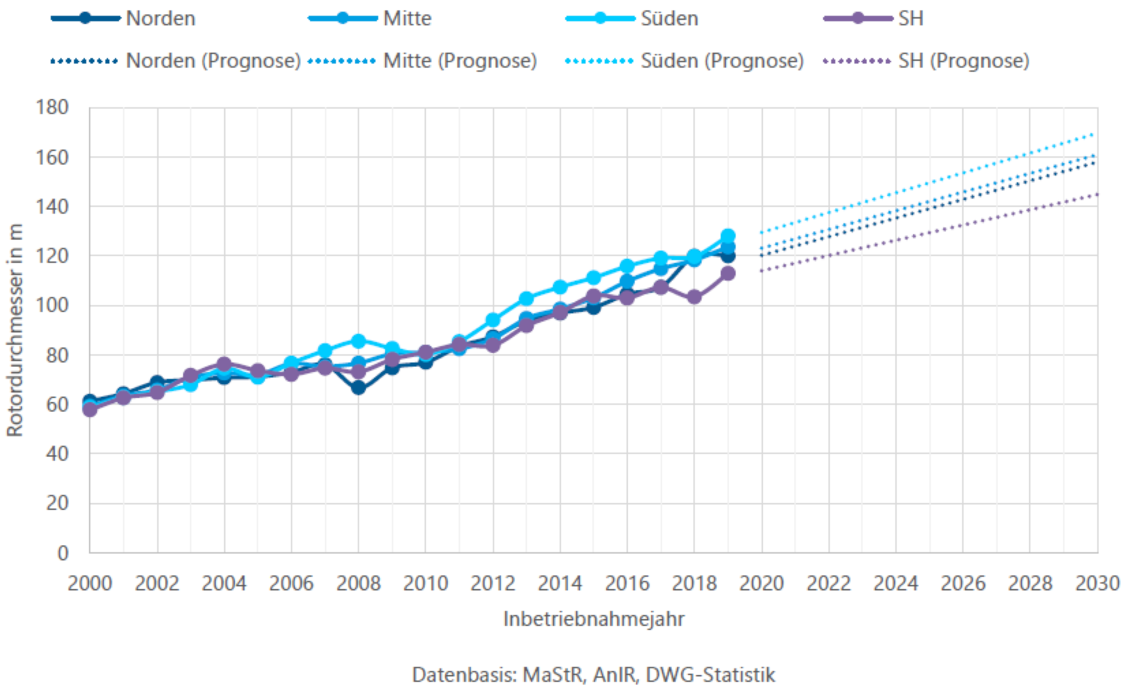

Figure 3: Development and forecast of the mean rotor diameter according to Deutsche WindGuard, 2020

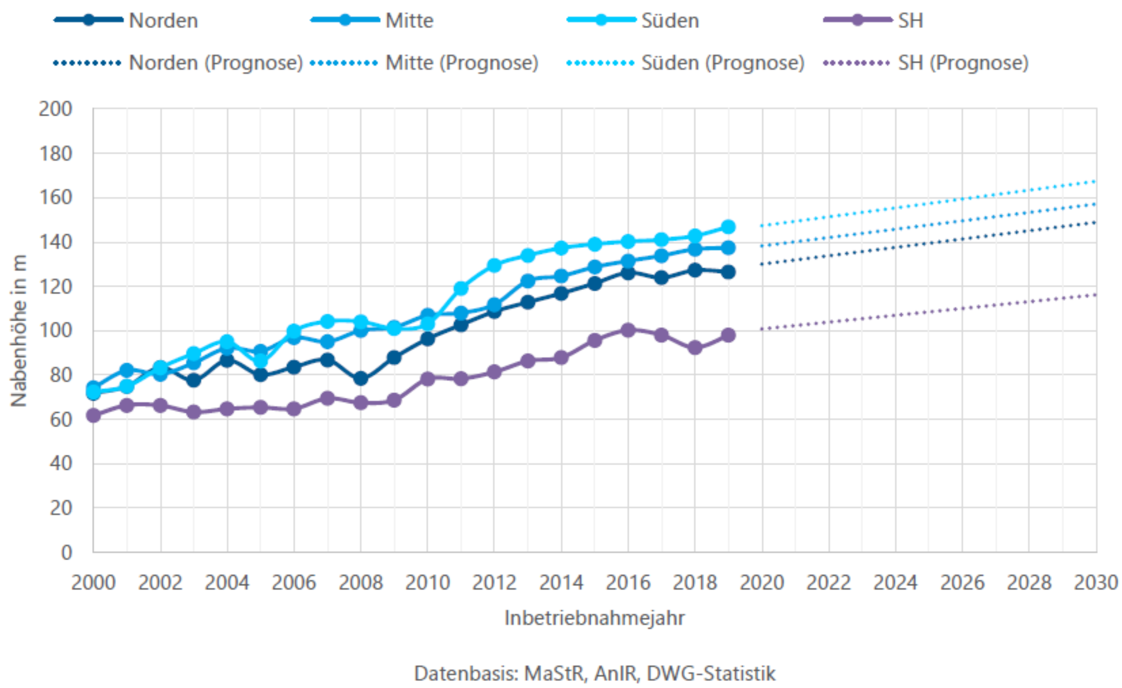

Figure 4: Development and forecast of mean hub hight according to Deutsche WindGuard, 2020

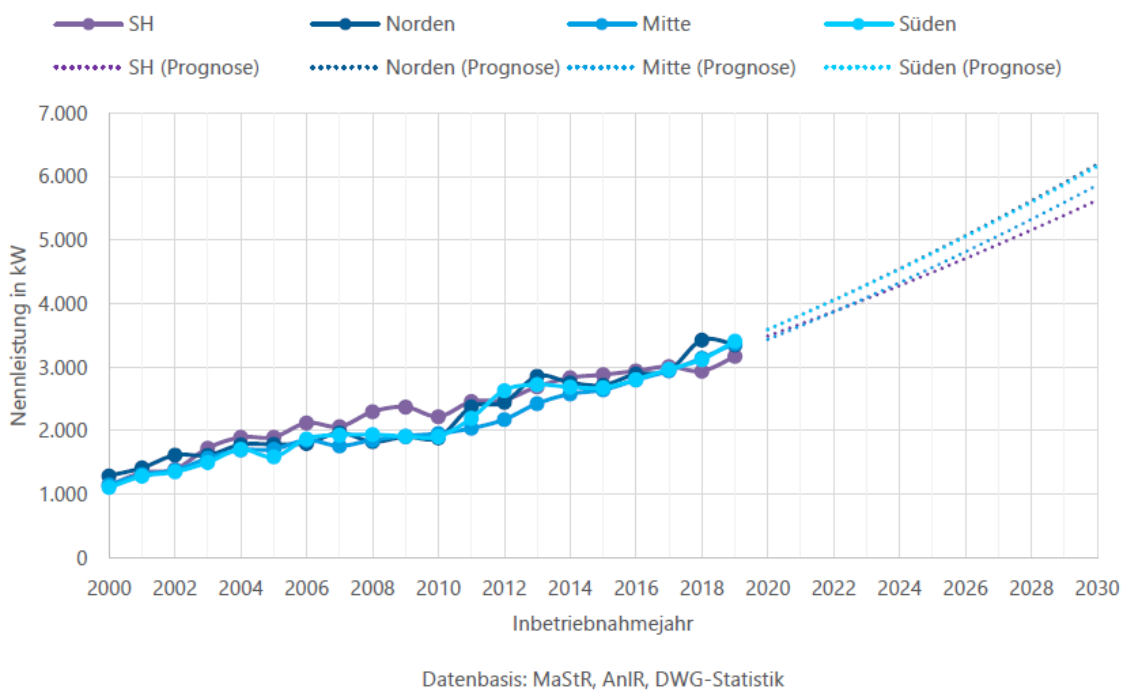

Figure 5: Development and forecast of the mean rated capacity according to Deutsche WindGuard, 2020

The full load hours number the hours that the system would have to be operated under nominal load in order to deliver the amount of electricity generated and do not reflect the actual operating time below nominal load. 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, the full load hours are a useful concept in order to be able to draw conclusions about the electricity yield and, therefore, analysis of the full load hours of RLP are presented in Section 3.2.3. The development of full load hours in Germany can be seen in figure 6. If two plants have the same hub height and the same rotor diameter, but a different nominal power, the less powerful plant, i.e. the plant with the lower **specific nominal power**, 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 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 3. 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 you compare two systems with the same rotor diameter, the system with a higher absolute and therefore also specific nominal output is always more expensive and is

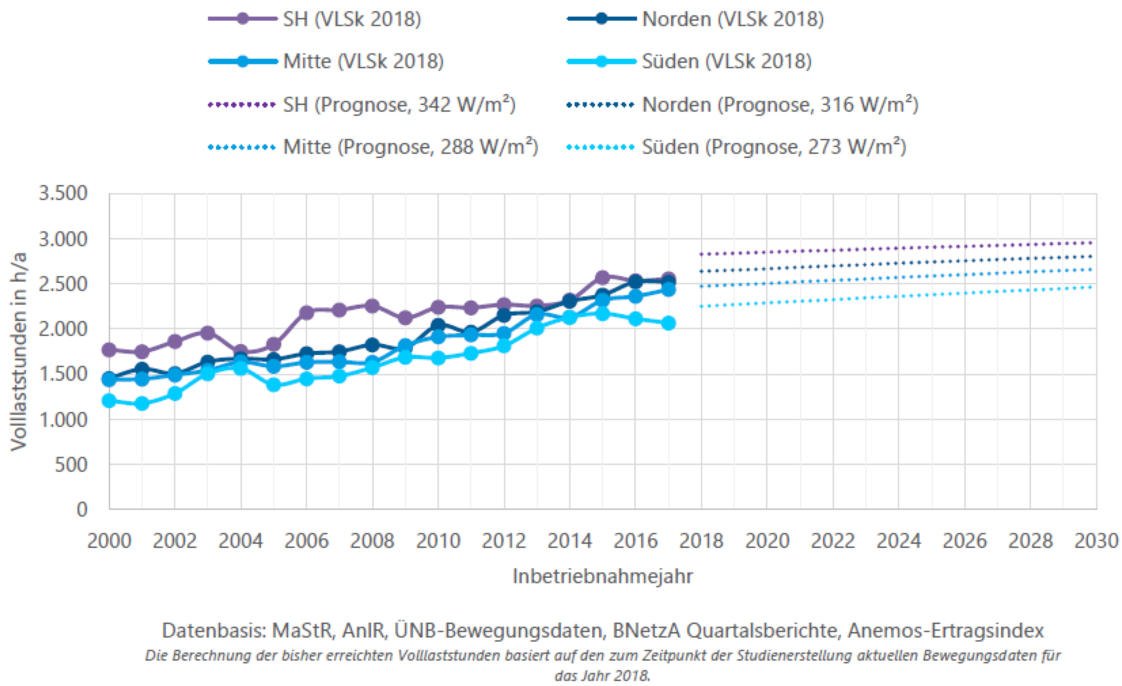

Figure 6: Development and forecast of the mean full load hours according to Deutsche WindGuard, 2020

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 seen in figure 7. 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. of a federal state, can be used as a parameter to infer the future electricity yield from the installed rated capacity.

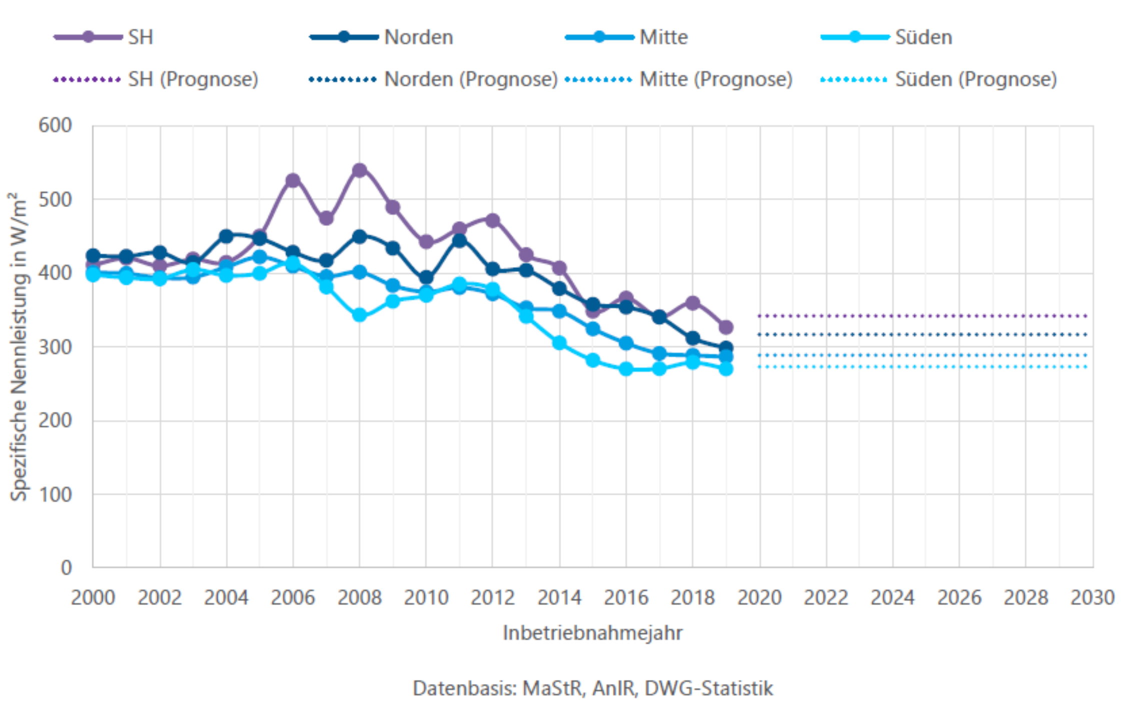

Figure 7: Development and forecast of the mean specific rated capacity according to Deutsche Wind-Guard, 2020

2.3 Onshore WT's and Repowering

2.4 Résumé

The study of DWG shows how the technology of onshore wind turbines has developed further 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 plants 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 WT's in RLP is beeing assessed using the market master data register.

3 Data

3.1 Materials

The Master and Movement data from the transmission system operator Amprion of the years 2017 to 2019 prepared by the energy agency of RLP is used to analyze the electricity yield mainly over the rated capacity and the commissioning date. Amprion lists 1,702 WT's in RLP in 2019. In comparison the Structure and Approval Directorate North registers 1,704 WT's with technical details and coordinate references that are connected to the public grid. In addition the Marked Master Data Register (MaStR) of the Federal Network Agency [23], in which all electricity and gas generation systems must be registered, is used. The MaStR contains technical details of the WT's and also the exact coordinate refernces of their location but not the electricity yield. The data from Amprion and the MaStR both contain a system key according to the Renewable Energy Law, by which they can be joined to a single data set which contains the electricity yield as well as the coordinates for the assessment of the area consumption per quantity of generated electricity.

For the preparation and the analysis of the data R version 4.0.5 (2021-03-31) – "Shake and Throw" and RStudio Version 1.4.1106 were used. Due to exhaustive code and iterative preparation steps the full documentation can not be displayed here but is to be found on `https://github.com/EliasCuadra/master-thesis-repowering` with explanatory README.md files that contain description of variables and processing steps. Nonetheless, important aspects or code chunks are directly included or can be found in the appendix.

3.2 Methods

3.2.1 Preparation and Analysis of data from the transmission system operator Amprion from 2017 to 2019

For the analysis only data from the years 2017 to 2019 is used because the WT technology is constantly improving and old data would not contain these new developments and therefore lead to an underestimation of future values. The data from Amprion comes with 28 or rather 27 variables for the year 2019 of which only some are interesting for the further analysis. The kept variables are: Community key, post code, place, rated capacity, commissioning date, system key and electricity yield. For the analysis of the electricity yield not all the WT's are meaningful and some outliers are removed from the data. On the one hand WT's 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 WT's are listed with a rated capacity up to 12 MW which might be because several WT's are registered as one. It is therefore assumed that if the rated capacity is larger than 4,5 MW it also does not reflect the average conditions, even though systems of this size exist. Also WT's that are build in the same year after the 15th of February are excluded since they have less time to generate electricity and therefore deliver misleading data. The data from 2017 show 1,623 WT's in total of which 101 are outliers. The data from 2018 show 1,674 WT's of which 76 are outliers. The data from 2019 show 1,702 WT's of which 46 are outliers. An interim result are three csv files of the different years that only have relevant variables in the correct format and are free of outliers. Only the data 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 are added. The data from 2019 is then divided in three files according to the commissioning date to find the WT's that are build either before 2005, before 2001 or between 2001 and 2005 and are therefore potentially suitable for repowering. A flow chart of the individual processing steps that have been performed is presented in figure 8. After the preparation, the data is firstly analyzed

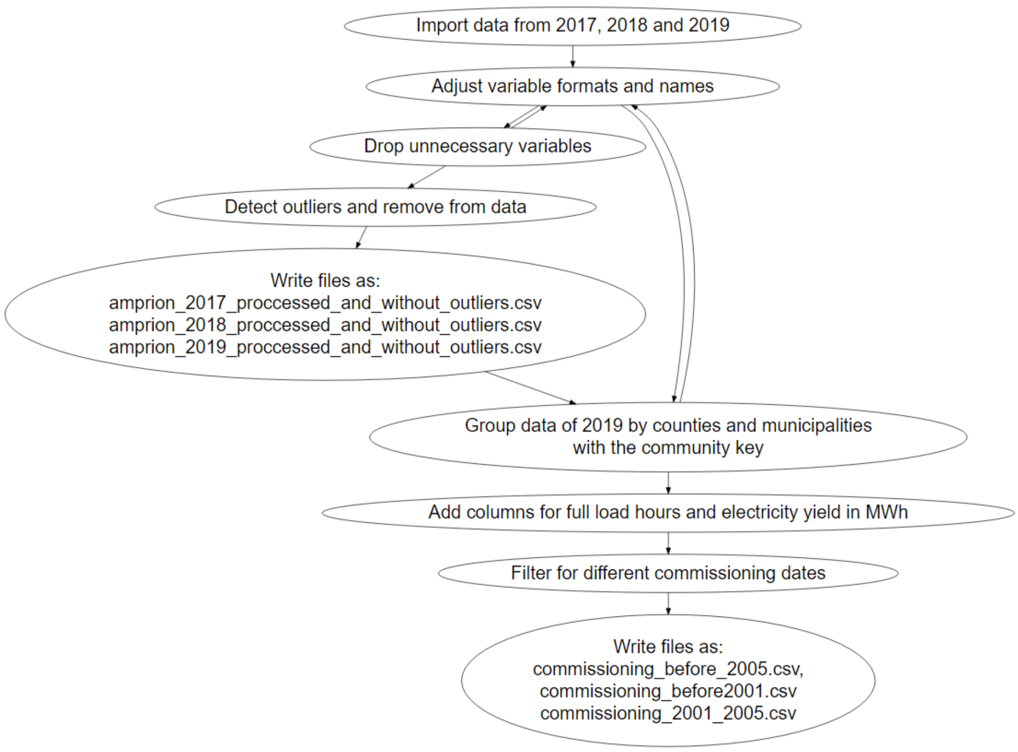

Figure 8: Flow chart of the proccessing steps

regarding the amount of electricity generated per WT and year. For this purpose, a linear and a 3rd order polynomial regression, that 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 WT's do not change over time. Further the full load hours as a concept of the degree of utilization is analyzed in regard of the WT's 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 can not be disregarded. Which means concrete that old data might still deliver a wrong impression on future predictions but also might account for weak years in terms of wind conditions since 2019 might be a stronger wind year.

3.2.2 Area consumption of WT'S in RLP

3.2.3 CO_2 reduction potential

3.2.4 Repowering potential

4 Results and discussion

The diagnostics of the electricity yield show in all linear and polynomial models the same characteristics even if slightly different the model assumptions are not fundamentally violated. In figure 9 the diagnostic plots of the electricity yield 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 WT 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 very 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.

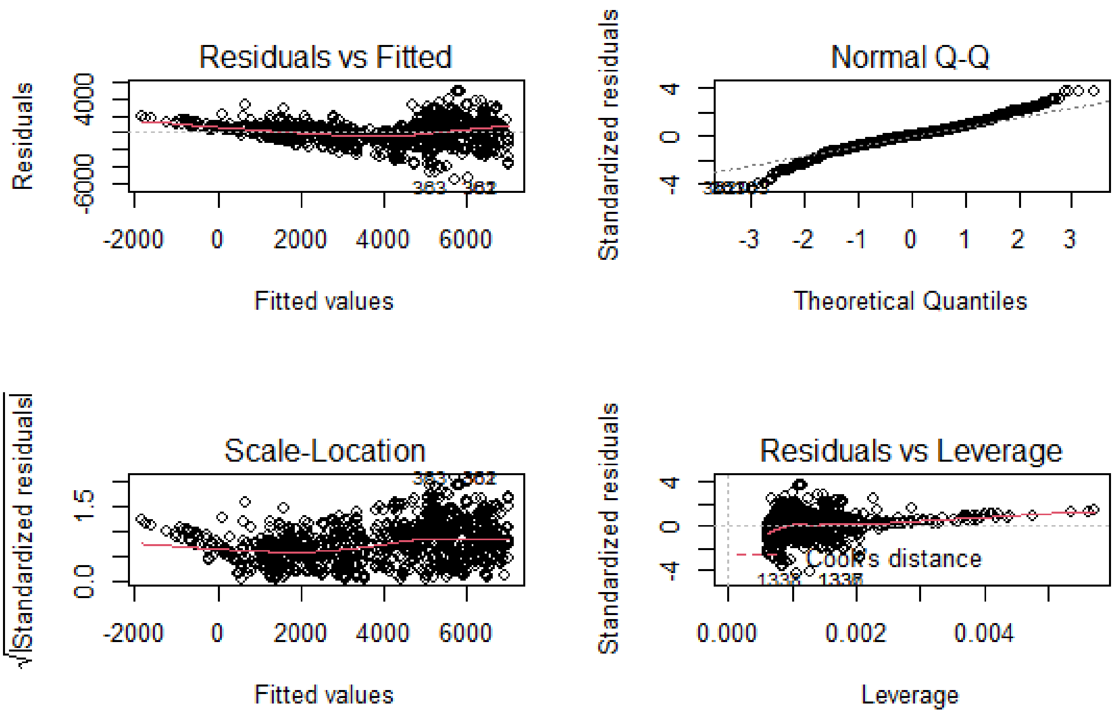

Figure 9: Diagnostic plots of electricity yield from 2019

All models are highly significant with p-values lower than 0.001 and the linear models have a R^2 value 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 loose 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 more reliable. However, the DWG forecast 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 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 10. For the given reason and to obtain a conservative estimate the average electricity yield in 2021 of the three linear trends which amounts to 7,400 MWh per WT is used for further calculations. For the following plots and

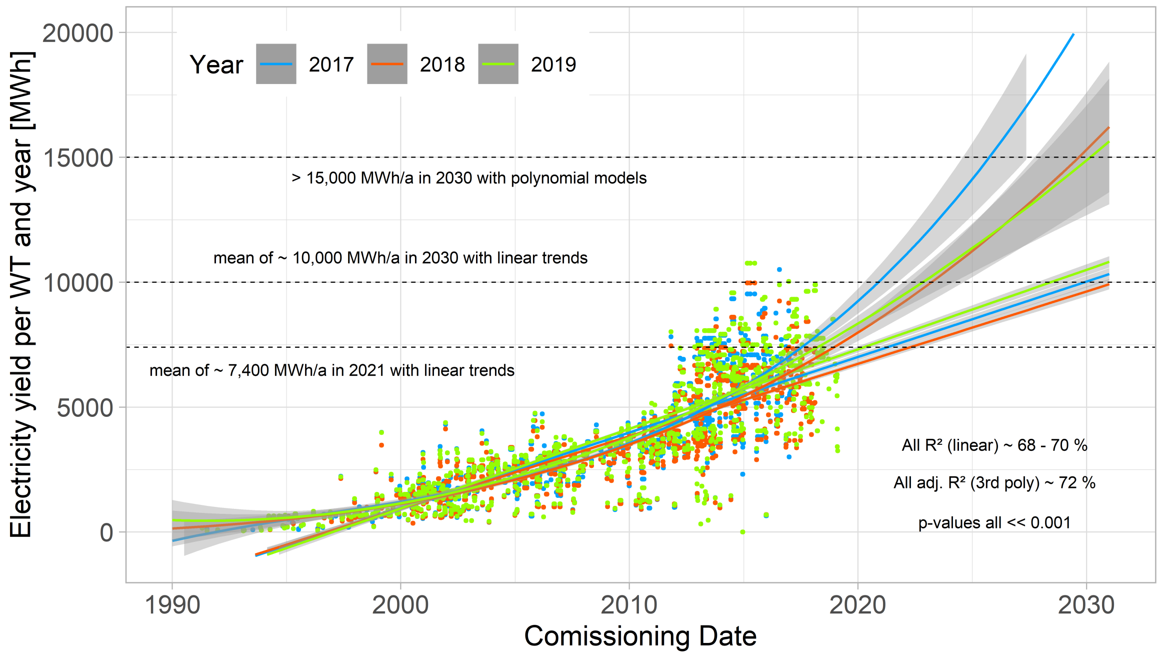

Figure 10: Development and forecast of electricity yield in Rhineland-Palatinate using data from 2017 to 2019 and a linear an polynomial model

trends the diagnostics and significance is 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 11. As expected the electricity increases with increasing rated capacity and therefore also more recent commissioning date because the size and generator technology advances continuously. 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. But not only the electricity yield increases also the variance increase. This is also logic since the different and fluctuating wind conditions lead to a greater magnitude of difference in electricity yield when using a larger generator. To generate the average electricity of 7,400 MWh/a that were presented before, as a minimum a 3.5 MW turbine must be used. Hence, this 3.5 MW are used for further calculations. The plot of the rated capacity over the commissioning date is shown in figure 12. It shows 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 an prediction for the year 2030 with 4,500 kW using a linear trend.

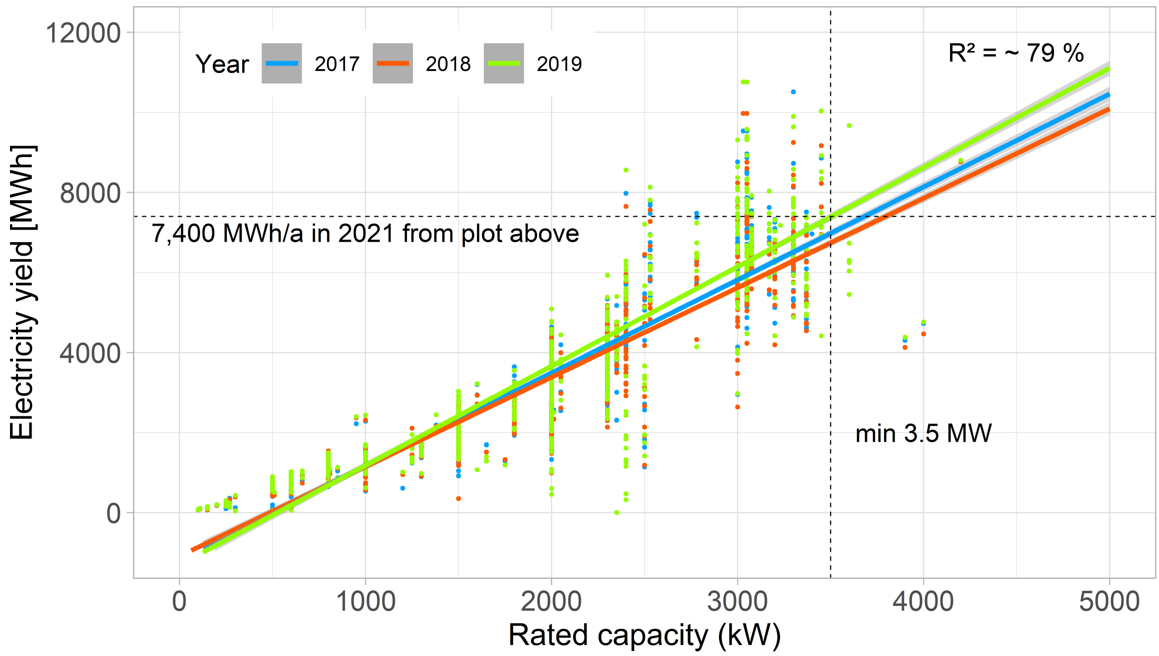

Figure 11: Electricity yield over rated capacity

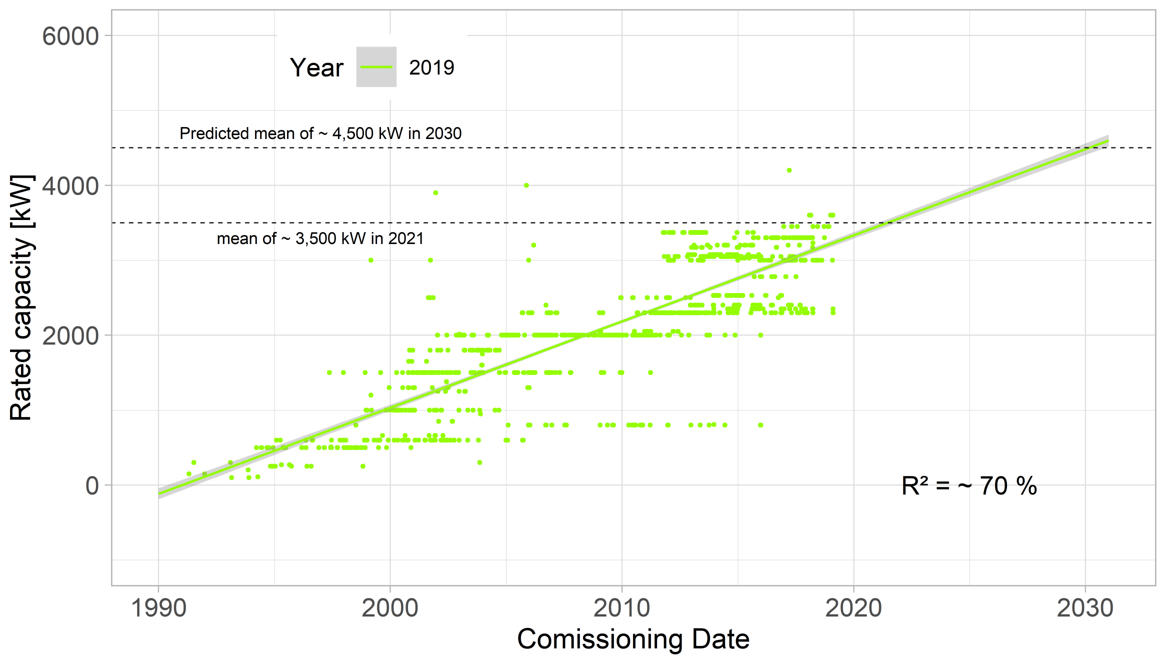

Figure 12: Rated capacity over commissioning date

5 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

Here goes the appendix!

A.1 Figures

A.2 Tables

	3m	6m	1yr	2yr	3yr	5yr	7yr	10yr	12yr	15yr
Mean	3.138	3.191	3.307	3.544	3.756	4.093	4.354	4.621	4.741	4.878
Median	3.013	3.109	3.228	3.490	3.680	3.906	4.117	4.420	4.575	4.759
Min	1.984	1.950	1.956	2.010	2.240	2.615	2.850	3.120	3.250	3.395
Max	5.211	5.274	5.415	5.583	5.698	5.805	5.900	6.031	6.150	6.295
StD	0.915	0.919	0.935	0.910	0.876	0.825	0.803	0.776	0.768	0.762

Table 1: Detailed descriptive statistics of location and dispersion for 2100 observed swap rates for the period from February 15, 1999 to March 2, 2007. Swap rates measured as 3.12 (instead of 0.0312).

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, July 12, 2021

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