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

Master's Thesis submitted

to

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Contents

Abstract

This master's thesis was written in the context of climate protection through the energy transition and with regard to the threat to people and the environment from the consequences of climate change. The initial question here is how can the temperature increase be limited to 2 °C above the pre-industrial level, as formulated by the Intergovernmental Panel on Climate Change (IPCC). There is consensus on the assumption that energy from wind plays and will continue to play a decisive role in avoiding fossil fuels and thus CO_2 emissions. This was the reason to examine the potential of wind power in Rhineland-Palatinate from 2021 to 2030 and to critically question the expansion goals and the climate protection goals of 2030. The central result of this work is that with a consistent and substantial expansion of wind power, an existing number of 2,500 wind power plants can be realized in Rhineland-Palatinate until the year 2030. This stock can contribute a quantity of 22 TWh to the total electricity demand and thus also make a substantial contribution to the achievement of the climate protection goals. It is even realistic, e.g. by designating additional areas, to increase electricity generation from wind power.

List of Abbreviations

IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse gas
RLP	Rhineland-Palatinate
TWh	Tera Watt hours
WT(s)	Wind turbine(s)
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 WindGuard
CRS	Coordinate Reference System
WGS84	World Geodetic System 1984

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1 Introduction

This thesis was done and written in scientific recognition of the effects of climate change as reported by the Intergovernmental Panel on Climate Change (IPCC) and the the importance of reducing greenhouse gas emissions to prevent a rising of the global average annual temperature below 2 °C [1]. To achieve this goal many countries around the globe put special effort in greenhouse gas reduction and the transformation of their industry. For the fulfillment of this purpose the Federal Climate Protection Act was passed in 2019 with latest changes in 2021 and states that the greenhouse gas reduction in comparison to the year 1990 should be at least 65% (formerly 55%) in 2030 and at least 88% in 2040 and from 2045 onward there should be a net greenhouse gas neutrality [2]. The tightening of these reduction targets came through the recent decision and the subsequent press release No. 31 from April 29, 2021 [3] of the first Senate of the Federal Constitutional Court which states that the regulations of 2019 on the national climate protection targets and the annual emission quantities permitted up to 2030 are incompatible with fundamental rights, as there are not 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 the adjusted edition of this act that strives for a faster development of renewable energies and the energy transition in general [4]. The central control instrument for the expansion of renewable energies is an will remain the Renewable Energy Act (EEG) with its latest edition of 2021. The aim of the EEG is to rebuild the energy supply and to increase the share of renewable energies in the electricity supply to at least 65% by 2030 and that all the electricity consumed and generated in Germany will be greenhouse gas neutral by 2050 [5]. The tools of the EEG are fixed feed-in tariffs for young technologies such as wind and solar energy to enter the market and guaranteed purchase and priority feed-in of electricity. From 2017, the level of remuneration for renewable electricity will not be set by the state, as was previously the case, but will be determined through tenders on the market to create a free market economy.

Similarly to the Federal law there is the State Climate Protection Act (Landesklimaschutzgesetz - LKSG) of Rhineland-Palatinate (RLP) that came into force on August 23, 2014 and states that the total of all greenhouse gas emissions in RLP 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% [6]. 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 [7]. This shows that studies focused on expanding renewable energies are very topical on a state level and also highly embedded in a dynamic socio-economic context.

Whether on a global, national or a local scale it is clear that a cornerstone of the transition of our society to an ecological sustainable form is the change of our fossil fuel based economy to an economy that is powered by renewable energies. Thus, the energy transition is regarded as the main focus 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 the research presented in this master thesis [8]. This study was carried out on behalf of the state-owned Energy Agency of Rhineland-Palatinate [9] within the project "Municipal Greenhouse Gas Accounting and Regional Climate Protection Portals in Rhineland-Palatinate" [10], which is funded by the European Regional Development Fund [11] and the state of 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.

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 [12]. By 2019, the electricity generated from wind turbines (WTs) had already increased to more than 6.7 TWh [13]. 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 [14], 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 [15], 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. The first option is to use areas that have already been identified as suitable for WTs but have not yet been built on, and the other option is that existing old systems whose absolute electricity feed-in quantity is low, can be replaced by new, taller and more efficient systems through 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 whether they are realistic and in line with the current distance rules and approval procedures and give recommendations for policy makers. Accordingly, the central questions of this work are:

1. How much electricity per area can be generated by a new WT from 2021 until 2030 in RLP?
2. What is the potential when all wind turbines built before 2006 are repowered?
3. How much area is needed to generate the target amount of 22 TWh?

This thesis will be organized into the following sections. Chapter 2 will introduce all of the necessary background information, including the scientific and technical fundamentals that are prerequisites for the assessment of the electricity yield from onshore WTs in RLP. In order to answer the research 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 (MaStR) are resented in Chapters 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 6.

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 basis 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.

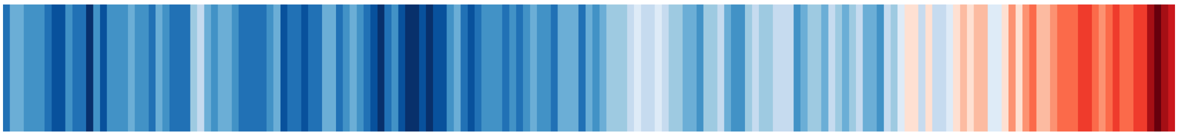

Figure 1: Warming stripes for 1850-2018 using the WMO annual global temperature data set [16].

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 [1]. 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 [17]. The Paris Agreement requires all 196 participating countries to declare their individual according efforts through Nationally Determined Contributions (NDCs). 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 65% compared to 1990. The law also formulates the goal of GHG neutrality by 2045. The biggest GHG emitter in Germany is the energy industry [18]. 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 [5].

2.2 Region of interest

This section highlights some characteristics of Rhineland-Palatinate (RLP), the region of interest for this study, since 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 but also plains areas. 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. RLP is the federal state with the largest area on the left bank of the river Rhine. The climate in RLP 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 land area [19]. RLP is one of the most densely forested states in Germany, with forests covering around 42% of the state's land [20]. The assessments and calculations required for this current study demand information about wind occurrence as well as the amount of electricity generation and data from existing WTs in RLP. An overview of important parameters regarding the estimation of the wind energy potential up to the year 2030 are shown in table 1. The study area and the modeled wind speeds taken from the Windatlas RLP [21] are seen in Figure 2.

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

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

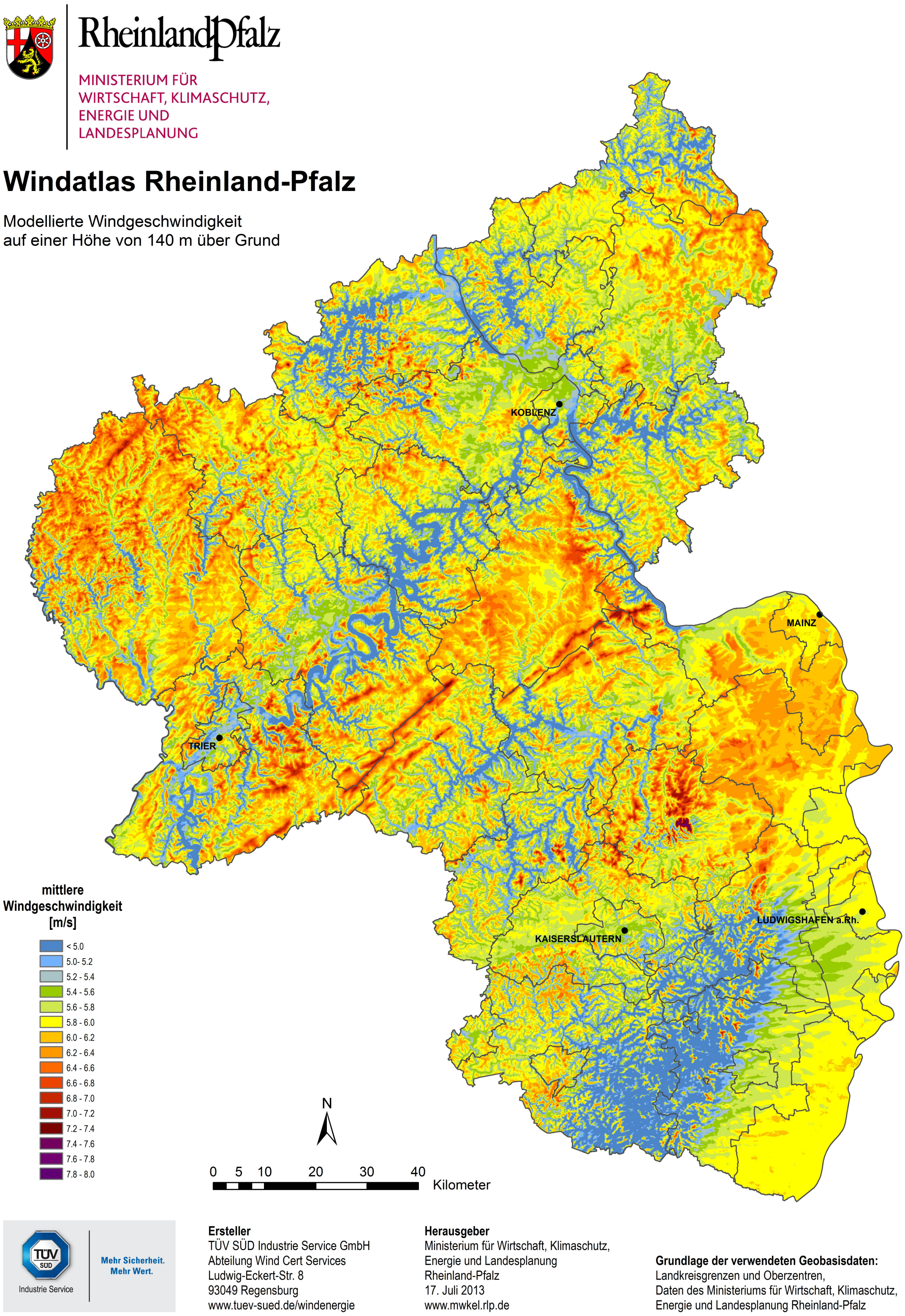

Figure 2: Wind speeds in RLP 140 m above ground [21].

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 blade angles through the so-called pitch control, thus protecting the system from damage but also increasing efficiency through optimal speeds. The avoidance of damage through peak loads due to high wind speeds can also be prevented through the stall effect but this requires complex aerodynamic design of the rotor blades. 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. Without going into the details of technical construction, the main components of the nacelle according to Vestas, one of the largest manufacturers of WTs is shown in Figure 3. 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].

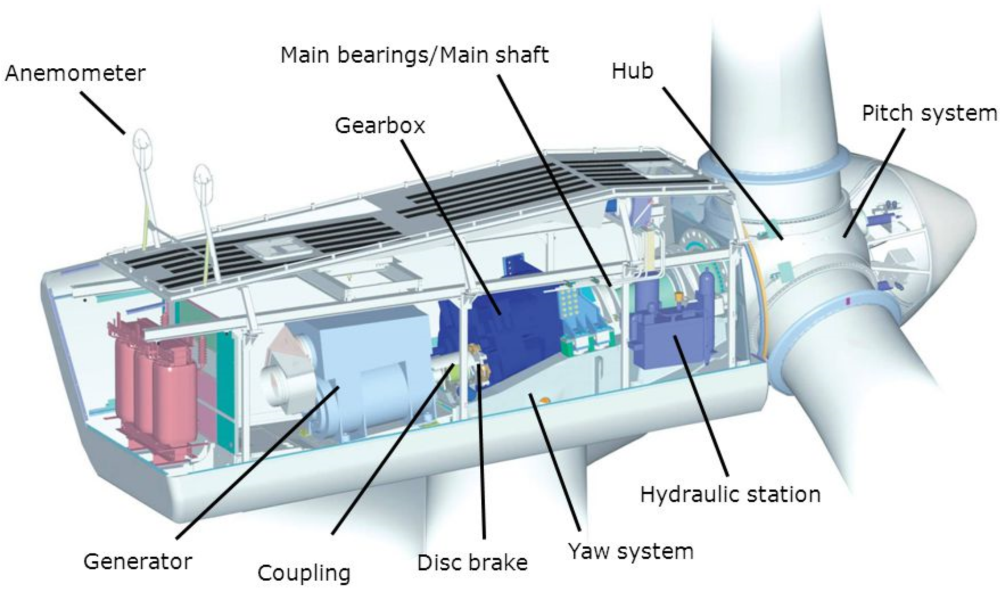

Figure 3: Main components in the nacelle (Vestas)

The expansion of wind power in Germany has slowed in recent years as can be seen in Figure 4, which details the development of onshore WTs according to Deutsche WindGuard. The service provider Deutsche WindGuard (DWG), which has been compiling a six-monthly expansion statistics since 2012, in the complex energy market stands for independent, manufacturer-neutral advice and comprehensive scientific, technical and operational services.

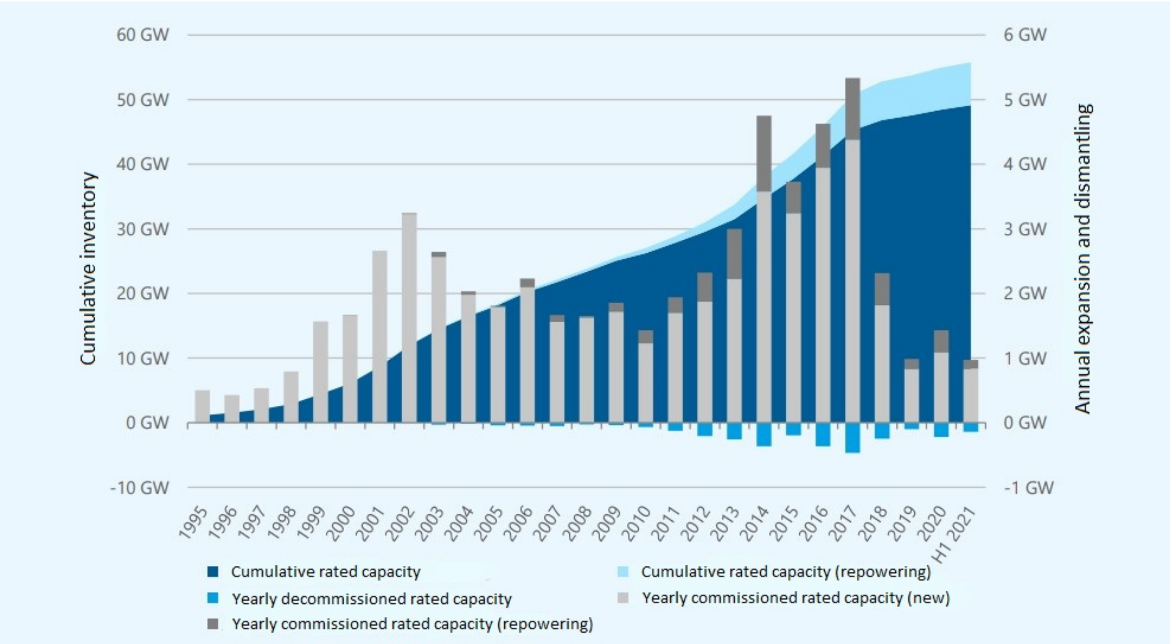

Figure 4: Development of expansion and dismantling of WTs in Germany from 1995 until 2021 [25].

As seen in Figure 4, in the first half of 2021, 240 new WTs with a rated capacity of 971 MW were installed in Germany. This corresponds to a 62% increase if compared to the first six months of the previous year. In the same period, 135 WTs with an installed capacity of 140 MW were shut down. The net expansion in the first half of 2021 is consequently 831 MW. The cumulative installed capacity increased by 1.5% to 55,772 MW as of June 30, 2021. A total of 29,715 onshore WTs are installed in Germany that provide this capacity. To achieve the expansion target for 2022 yet another net addition of around 1.2 GW is required. The target for 2030, which originates from the EEG 2021 is 71,000 MW. This number is not yet adapted by the expected increase in electricity demand in 2030. Another important player in the onshore wind energy industry is the Bundesverband Windenergie e.V. (BWE) as a member of the Federal Renewable Energy Association (BEE). The BWE represents the entire wind energy industry with its more than 20,000 members. Together, the supplier and manufacturing industry anchored in German mechanical engineering, project planners, specialized lawyers, the financial sector and companies from the fields of logistics, construction, service / maintenance and storage technologies, electricity traders, network operators and energy providers ensure that the

BWE is available to all questions relating to wind energy and is the first point of contact for politics and business, science and the media. The production of WTs can usually be realized within a few months with relatively little material and energy consumption. After a short period of operation, a WT has already "brought in" the energy that was required for its production. This period is known as the energy returned on energy invested (ERoEI) or, more simply, energy return on investment (EROI) and is for WTs on land between three and seven months. Offshore systems with an even higher rated capacity need four to five months to recycle the energy used in production and installation. Due to this relatively short energetic amortization, every operating hour delivers "net" clean electricity for an average of at least 20 years [26]. In comparison, photovoltaic systems need between one and four years for this energetic amortization. A wind power plant can therefore provide 40 to 70 times more energy during its entire life cycle than was expended for its manufacture, use and disposal, depending on the design. If this amount of electricity replaces fossil fuels, the wind power plant can credit itself with the avoided emissions from coal and gas power plants. Of course WTs are not entirely free of emmissions but the whole amount of CO_2 equivalent of a WT is about 10.6 g/kWh according to Memmler et al. [27] and about 400 g/kWh in the federal electricity mix [28]. After dismantling the old WT, a new one can be built in the same location or at least in the same area. This is referred to as repowering. The development of repowering processes according to DWG is shown in Figure 5.

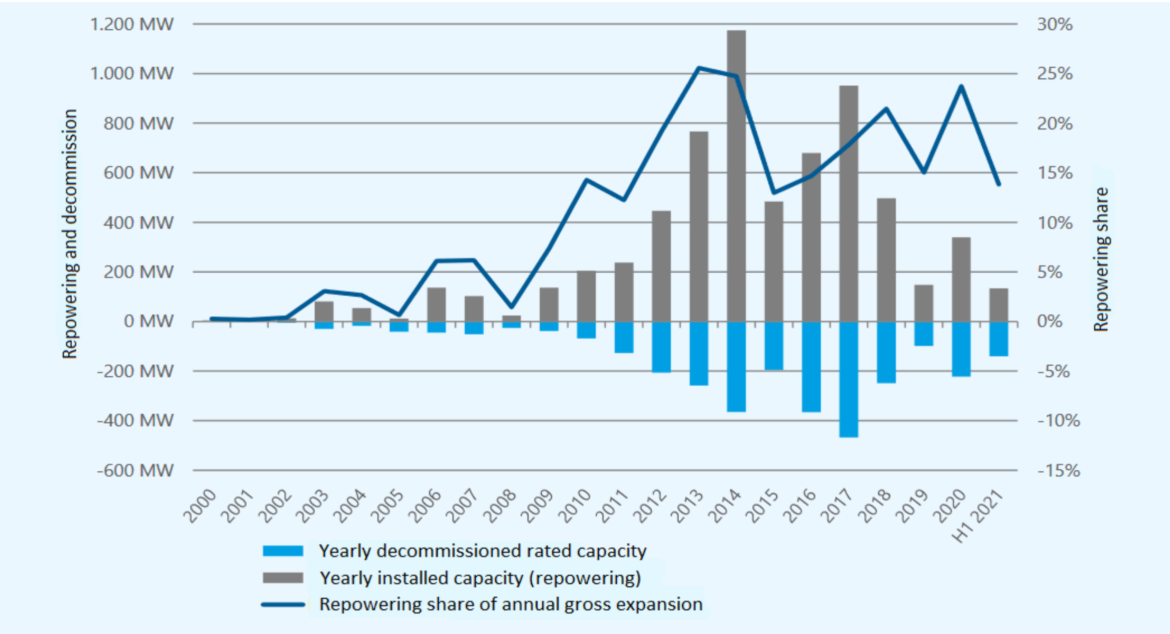

Figure 5: Development of the annual and proportionally installed and reduced capacity within the scope of repowering projects [25].

The electricity generation from wind energy in RLP can be traced by using data from the transmission system operators. In the case of RLP it is the transmission network operator Amprion, who publishes 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 Renewable Energy Act (EEG) 2017 [29]. 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 approximately 6.782 TWh [30]. The average electricity output in RLP of one WT was about 7,000 MWh in 2019 but newly commissioned WTs already have an output of more than 10,000 MWh which would be sufficient to cover the demand of 2,500 households (4,000 kWh). However, looking at current product brochures of large manufacturers, such as Vestas, Nordex or Simens Gamesa, the development potential of WTs is not yet exhausted. The annual generation of electric energy of a Vestas V162 with a nominal output of 5.6 MW, hub height up to 166 m, rotor diameter of 162 m and a swept area of 20,612 m² is shown in Figure 6. Nordex has a similar model called N163/5.X with a nominal output of 5 MW and more, a hub height of up to 164 m, rotor diameter of 163 m and a swept area of 20,867 m² [31]. Practical experience from project developers show that wind parks with an estimated commissioning in 2025 are already planned with the next generation of onshore WT that have over 6 MW nominal power. But even now a product of Simens Gamesa called SG 6.6-170 has a nominal power of up to 6.6 MW, a hub height of up to 165 m, a rotor diameter of 170 m and a swept area of 22,697 m² [32]. This means that the expected annual output of WTs in RLP with an average wind speed of 6 m/s can be estimated with relative certainty to be 15 to 20 GWh within the next ten years.

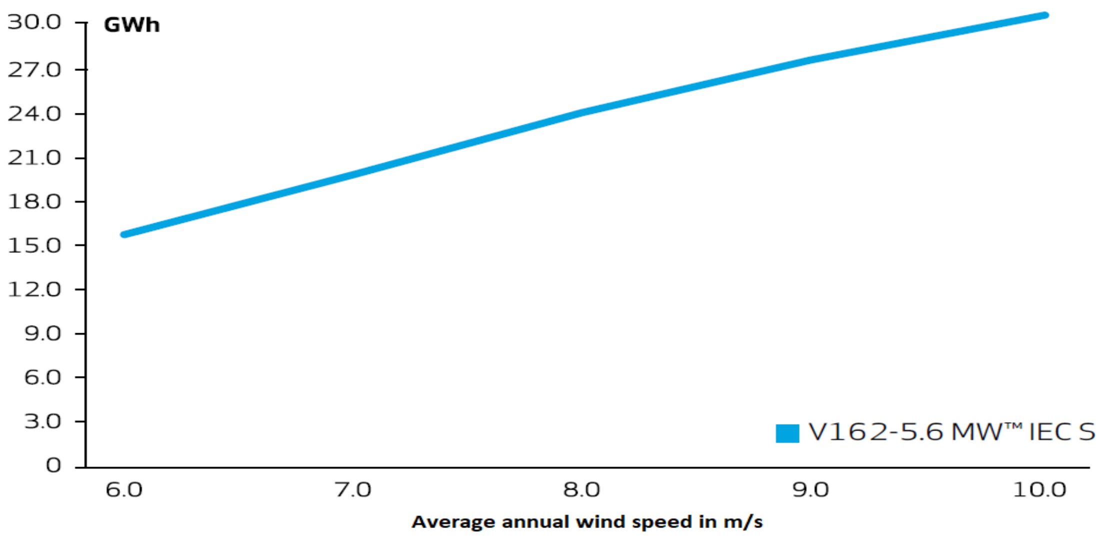

Figure 6: Annual energy production of a V162-5.6 IEC S in relation to the wind speed [33]

2.4 Spatial planning in RLP

The decisions of whether new WTs should be built depends heavily on the spatial planning and the respective regulations and laws. Therefore the different planning levels in RLP are presented in the following sections and the procedure for an aproval process is outlined roughly.

2.4.1 State level

As the highest planning authority in RLP in terms of spatial planning, the Ministry of the Interior and Sport acts and thus ensures a fair balance between the various demands on the use of space as a resource. The state planning thus acts as a neutral mediator and moderator to ensure sustainable development of the state of RLP and the requirements of the state government for a social and ecological transformation regarding sustainable economic development, social integrative cohesion and responsibility for the environment reconciled. The state planning controls the comprehensive, regional and interdisciplinary planning for the state [34]. The main legal bases of spatial planning in RLP are the federal Spatial Planning Act (Raumordnungsgesetz - ROG) and the State Planning Act (Landesplanungsgesetz - LPlG)[35]. The Spatial Planning Act primarily contains the basics of the procedure for drawing up statewide and regional spatial plans, the legal effects of the plan content, and the procedure for examining projects that are of spatial importance. The State Planning Law only has a supplementary function compared to the Spatial Planning Act. It regulates in detail the preparation of spatial plans, the implementation of spatial planning procedures and the organization of regional planning in RLP. An amendment to the State Planning Law recently made it possible for recognized nature conservation associations to be accepted as members of the regional planning communities [36].

The 2008 version of the State Development Program IV (Landesentwicklungsprogramm IV) from 2008 with several updates forms the coordinating and interdisciplinary spatial framework for the development of the state of RLP and specifies goals for the development of the infrastructure [37]. Regarding wind power, the first partial update of the State Development Program IV stipulated that an orderly expansion of wind power should be ensured through regional and urban land-use planning. For the purpose of of identifying priority areas for the use of wind energy, the authority for a final control through the designation of concentration areas for wind energy was transferred to the land-use planning and the regional plans. The basic distribution of tasks between state planning, regional planning and land-use planning is retained in the third partial update of the State Development Program IV from 2017 [38]. In order to ensure an appropriate balance between the expansion of wind energy on the one hand and the requirements of nature, landscape and cultural landscape protection as well as the needs of the population on the other hand, adjustments through an immediately applicable change are being made in the partial update of the State Development Program IV. The main innovations that are designated to give substantial space to the expansion of wind energy, with the 2% target in mind, and give special support for the repowering of old systems, taken from the Ministry of the Interior and Sport are [38]:

The following exclusion criteria for WTs apply:

- In nature reserves and areas with contiguous hardwood stands over 120 years old
- In the Palatinate Forest Nature Park, national parks and core zones of nature parks
- In the core zones and in the framework areas of the UNESCO World Heritage Areas Upper Middle Rhine Valley and Upper Germanic-Raetian Limes
- In nationally significant historical cultural landscapes of assessment levels 1 and 2
- In those Natura 2000 areas for which the state bird sanctuary for Hesse, RLP and Saarland and the State Office for the Environment, Water Management and Trade Supervision in the "nature conservation framework for the expansion of wind energy in RLP" have identified a very high potential for conflict
- In water protection areas of zone I

Modification of area specifications. The requirement to provide two percent of the land area for the use of wind energy (Principle G 163 a) is retained in principle, but the formulation as a minimum proportion is dispensed with the deletion of the term "at least." The same applies to the provision of forest areas (principle G 163 c).

Minimum area size: systems in a spatial network. The requirement that wind turbines may only be erected at locations where it is possible to build at least three systems in a network is becoming a legally binding goal (previously G 163 f, now Z 163 g). In the case of repowering, it is sufficient to erect at least two turbines.

Minimum distance to areas with residential use. Required minimum distance from wind turbines of 1,000 meters to pure, general and special residential areas as well as to villages, mixed and core areas and a minimum distance of at least 1,100 meters for systems with a total height of more than 200 meters (Z 163 h). Falling short of the distances is only permitted in the case of the particularly desired repowering of old systems (Z 163 i) [38].

2.4.2 Regional level

Regional planning agencies are the planning communities for the regions Middle Rhine-Westerwald, Trier, Rheinhessen-Nahe, West Palatinate and the Association Region Rhine-Neckar for the metropolitan region Rhine-Neckar (section 12-15 State Planning Act RLP (LPlG)). The planning communities are made up of the independent cities and districts in the area of a region. In RLP, there are regional spatial plans in four planning regions and one transnational metropolitan region. These are currently being updated taking into account the content of State Development Program IV and are thus adapted to the current regulatory situation and are used to concretize the given specifications for the respective planning region [38].

2.4.3 Local level

According to Section 5 of the Building Code (BauGB), the land use plan for the entire municipal area must outline the type of land use resulting from the intended urban development according to the foreseeable needs of the municipality [39]. It is a graphic plan representation of the entire municipal area, in which the existing land uses and those desired for the future are shown. For example, residential areas, commercial areas and arable land are displayed. This applies to areas on which these uses already exist and areas on which this use is to be established in the future. The purpose of the zoning plan is not a cartographic representation of the current situation, but rather a conceptual development plan directed towards the future. Therefore, the planning representations deviating from the actual state represent the essential content of the zoning plan, although usually occupy a much smaller area than the existing representations [38].

The zoning plan is therefore of particular importance for the designation of new building areas or concentration zones for wind power plants according to Section 5 (2b) of the BauGB. Positive location assignments at one or more places in the area of the administrative community mean that the remaining planning space is kept free of wind turbines and a uniform landscape is maintained, because according to Section 35 (5), a wind turbine is generally to be given preferential approval if public interests do not conflict and adequate development is assured. The exact land-use planning in a municipality is then regulated by the so-called development plan. It contains the legally binding stipulations for the urban planning order of part of a municipality and forms the basis for further measures required to implement the building code (Section 8 (1) BauGB) [39].

2.4.4 Approval

The approval of wind turbines takes place in the approval process according to the Federal Immission Control Act (Bundesimmissionsschutzgesetz - BImSchG). This is always necessary for wind turbines over 50 meters in total height. This will ensure that no harmful environmental effects or other dangers can be caused by the planned project and the project does not conflict with any other public law concerns. If this is guaranteed, the applicant has a legal right to be granted the permit (section 6 BImSchG) [40]. The district administrations or the city administrations are responsible for issuing the immission control permit. The immission control approval procedure has a concentration effect (section 13 BImSchG). This means that the other permits and approvals required for the operation of the system are also checked and approved as part of the immission control procedure. When approving wind turbines, in addition to the issue of immission control, the focus is particularly on the provisions of nature and species protection law, building regulations and building planning law. In addition, other technical issues such as aviation law or landscape and monument protection can be relevant. The technical assessment with regard to noise, shadows, operational safety and occupational safety is carried out by the structure and approval departments (Struktur- und Genehmigungsdirektion - SGD) [41].

2.5 Energy policy program

In the newly formed coalition agreement of the government of the federal state of RLP from 2021-2026, the goal of 100% renewable energies in the electricity mix by 2030 is reaffirmed and stated: “We will vigorously expand wind power and solar energy in order to double the installed capacity for wind power… by 2030.” ”This means the net expansion of 500 megawatts of photovoltaics and **500 megawatts of wind power per year**. In addition, the goal of 100% renewable energies in the electricity mix should be anchored in the Climate Protection Act". It is further stated that [42]:

- The rigid concentration offer in the State Development Plan IV should be abandoned, while continue to strive to establish larger wind parks
- The sum of the rated capacity after a repowering must at least reach the sum of the output that was generated by the old system, which should nonetheless enable to reduce the number of WTs in one location
- The working with fixed distances rules, which should be 900 m for newly approved WTs and a 20% reduction for repowering systems, should continue.
- The regulation in the State Development Plan IV (Z.163h) that the minimum distance to pure,

general and special residential areas, village, mixed and core areas must be observed. The rule-exception principle applies to WTs in the core zones of nature parks. The core zones are generally excluded for WTs. A case-by-case examination should be possible where the protection goal is not significantly disrupted.

- The medium-term goal within this legislative period is to review the nature conservation core zones and to adapt the associated ordinance.
- It should be checked whether pre-polluted areas (railway lines, motorways, conversion areas) in the area of nature parks can be freely built upon [43].

2.6 Climate protection concept RLP

The Ministry of the Environment, Energy, Food and Forests of RLP first published a climate protection concept in 2015 with a latest update from 2020. The concept sets out the initial situation in form of a greenhouse gas emissions balance as well as the options for action and names almost 100 measures from eight fields of action in a catalog of measures with which the country's climate protection goals are to be achieved [44].

Catalog of measures: In order to implement the state's climate protection and energy goals of 100% renewable electricity generation by 2030 (most recently confirmed by the state parliament resolution of April 26, 2018) with special respect to the transport and heating sector, further expansion of the use of wind energy is essential. According to the previous expansion forecast for wind energy in RLP, and if the corresponding regulatory framework conditions are created by the federal government, a total of **2,500 plants with a total output of 8,900 MW** and a contribution to renewable electricity generation of 18.7 GWh will be expected in 2030. The expansion of wind energy has declined sharply in the last two to three years. The reasons for this are diverse and relate to deficits in the EEG 2017. Increasing complexity and duration for the planning of new construction projects, as well as approval hurdles and increasing protests in many places lead to litigation. In order to remove existing obstacles and to promote the necessary expansion of wind energy use, in particular repowering projects, whereby several old systems are replaced by a few more powerful systems, the state will advocate the further development of statewide and nationwide framework conditions. Concrete measures for this are:

- Facilitation of repowering projects in the existing legal framework especially the Federal Immission Control Act (Bundesimmissionsschutzgesetz - BImSchG). Repowering results in a reduction in the number of installed wind turbines in one location and thus a reduction in imissions when the output is increased. The dismantling of obstacles to approval in the case of new planning and repowering should also be taken into account. For this purpose, the following measures are to be implemented in accordance with the resolution of the heads of government of the federal states of June 17, 2020 [44]:

1. Needs-based personnel and technical equipment of the planning and approval authorities
2. Approval structures as central as possible per country
3. Shortening of instances (the higher administrative courts are to decide in the first instance on disputes in the approval procedure)
4. Elimination of the automatically suspensive effect of objections and lawsuits against approvals
5. Establishment of a central advice center
6. Conservation-related standardization to simplify the enforcement of species protection law when a permit is issued

- Commitment of the state for a continuous further development of the Renewable Energy Act, especially in relation to the compensation of the location-related disadvantages of wind energy locations in countries remote from the coast. Preservation of the diversity of actors and simplification of models for self-supply and direct supply through EEG surcharge relief if no EEG remuneration is used, as well as the implementation of the European Renewable Energy Sources Directive (REDII) in German law.

- Development of framework conditions, information and advice with regard to new business models, such as Power Purchase Agreements (PPA), longer-term electricity supply contracts between system operators and electricity consumers (e.g. industry or energy supply companies), in particular as an option for the continued operation of wind turbines with ending EEG remuneration and as an alternative business model for EEG remuneration for new systems. It is also important to adapt the EEG to abolish the EEG surcharge on self-supply and direct supply with wind energy electricity (not EEG-remunerated) by the federal government. [45]

2.7 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 relationship applies[1]:

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

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, wind speed and the time interval required[2]:

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

The power P is equal to the energy per unit of time $\hat{E}$. The following equationvgives the power of the wind[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 [46] and BWE [47])

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 7. 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]:

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

[1] $E_{kin} = kinetic\ energy,\ m = mass\ of\ air,\ v = wind\ speed$
[2] $\rho = density\ of\ air,\ A = rotor\ area,\ t = time$
[3] $r = radius\ of\ rotor,\ \pi = pi$
[4] $W = Watt$

The curve of power per m^2 in relation to the wind speed is also shown in Figure 7. 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.

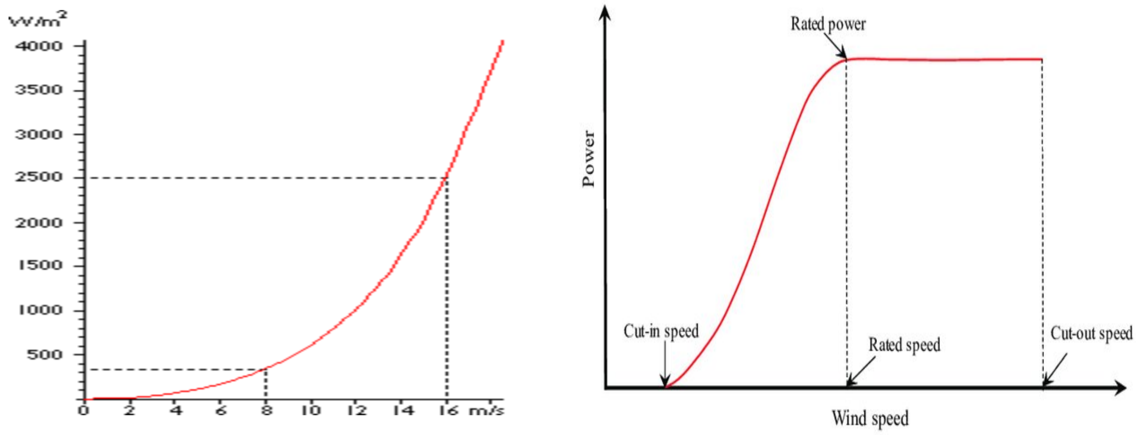

Figure 7: Left: Power of the wind per rotor area over wind speed [48]; Right: Typical load profile of a WT [49].

The maximum theoretical efficiency obtained for wind turbines is 59% according to the Betz Limit [50]; however, in practice it is often around 40% up to a maximum of 50% [51]. If the average rotor diameter installed in RLP in 2020 is 130 m (Figure 10) with an efficiency of 50%, then the average power of one WT is[5]:

$$
\begin{aligned}
P_{WT} &= 0.5 * \frac{1}{2}\rho v^3 * \frac{\pi}{4}d^2 \\
P_{WT130} &= 70\ W/m^2 * \frac{\pi}{4}(130m)^2 = 929\ kW = 8,138\ MWh
\end{aligned}
\tag{5}
$$

The amount of energy also increases proportionally with increasing rotor diameter which explains why the rotor diameters become larger in practice (Figure 10). If we assume a rotor diameter of 162 m of a modern WTs the power output increases up to 1,442 kWh which equals to an electricity yield per year of 12,639 MWh. It is said that large WTs with larger rotor diameter 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 [46].

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

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 RLP assuming an average wind speed of about 6 m/s. If we reduce the distance of each WT to 3 times the rotor diameter the output increases to around 6.1 W/m^2. 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 [52]. 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 11). 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 [46]. 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:

$$A_{22TWh} \; = \; \frac{22 * 10^{12} \; Wh}{2.2 \; W/m^2 \; * \; 8760h \; * \; 10^6} \; = \; 1140.9 \; km^2 \tag{7}$$

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 Chapters 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 methodology, the study of the German WindGuard (DWG) "Full-Load-Hours Of Wind Turbines On Land - Development, Influences, Effects" from October 5th, 2020 [53], is used as a guide and the relevant results are presented in the next subsection.

2.8 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) [53]. 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 per year are calculated from the quotient of the annual energy yield and the nominal output also called as rated capacity, which means 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 forward-looking 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 8. The graph shows an average of around 2,050 h for the south of Germany in 2017 with a predicted increase up to around 2,450 h in 2030.

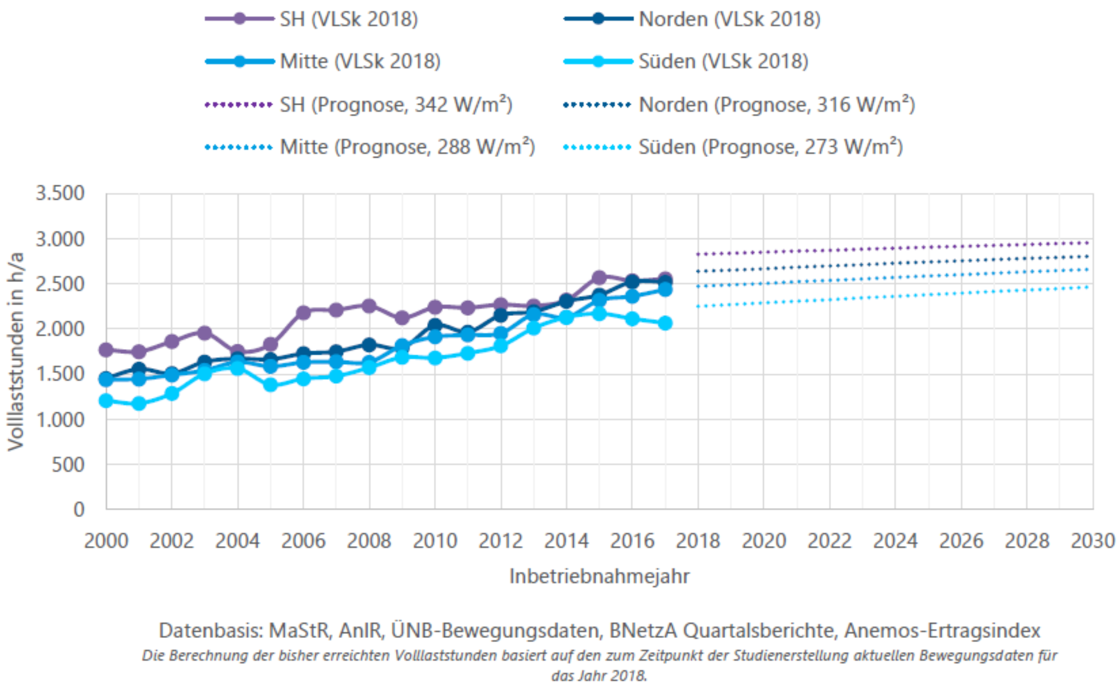

Figure 8: Development and forecast of the mean full-load-hours (in h/a) for WTs installed in Germany. Figure taken from Deutsche WindGuard 2020 [53].

The study of DWG suggests that the wind energy potential, i.e., the theoretical electricity 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 9.

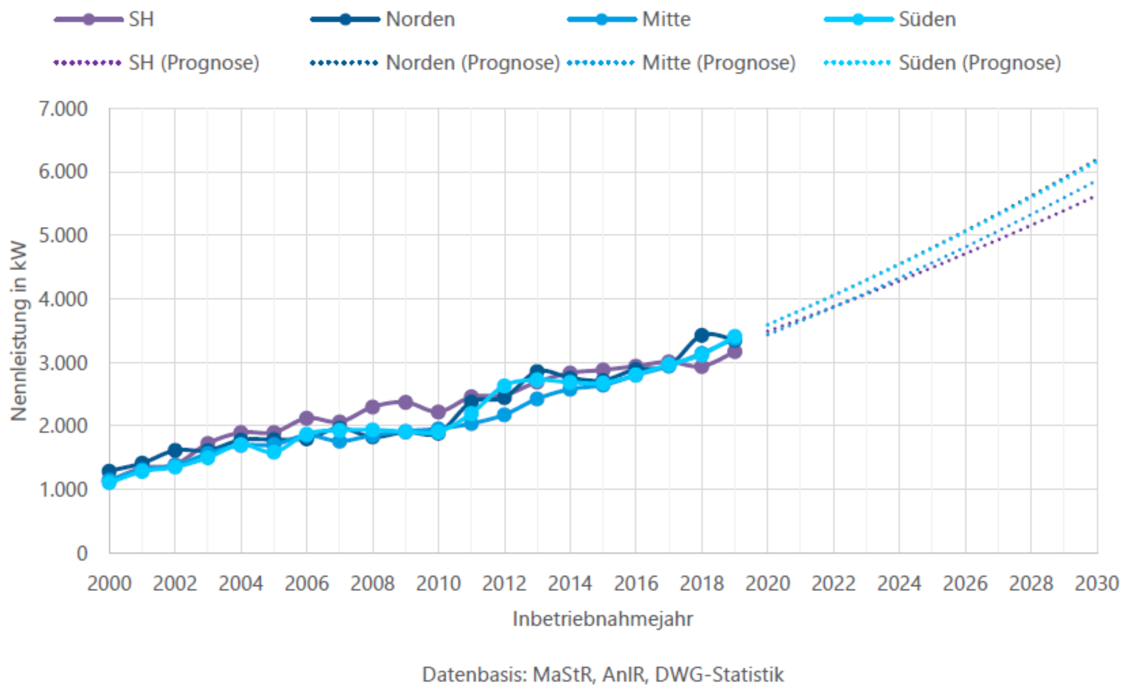

Figure 9: Development and forecast of the mean rated capacity (in kW) for Wind turbines installed in Germany. Figure taken from Deutsche WindGuard 2020 [53].

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 10 and 11.

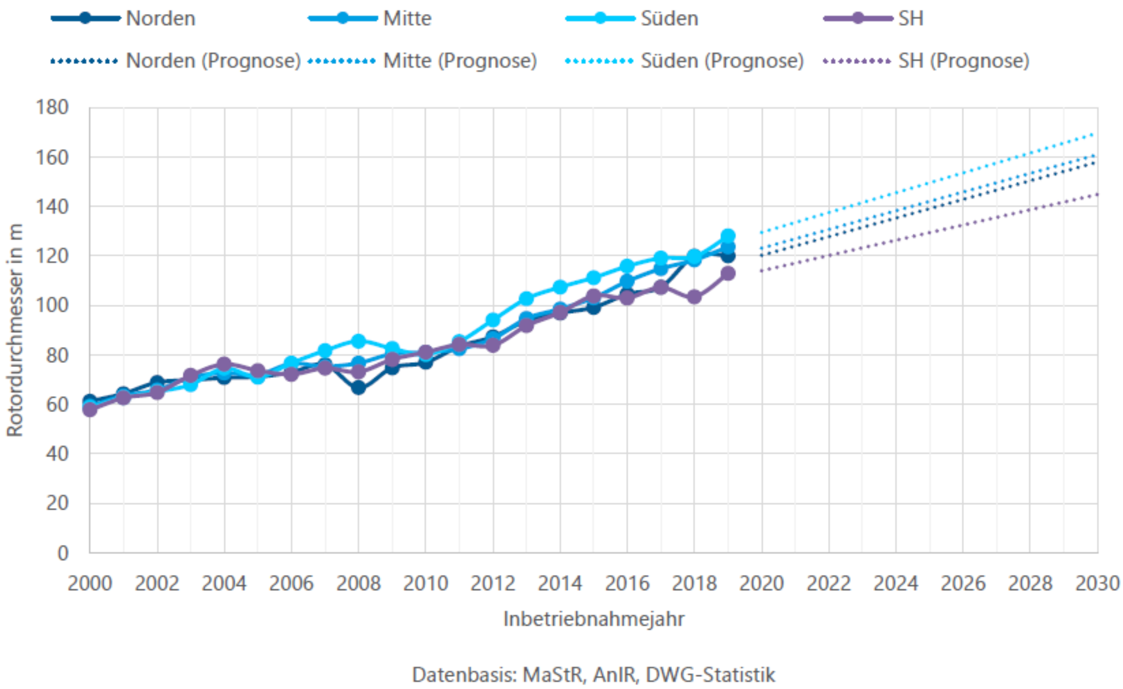

Figure 10: Development and forecast of the mean rotor diameter (in m) for WTs installed in Germany. Figure taken from Deutsche WindGuard 2020 [53].

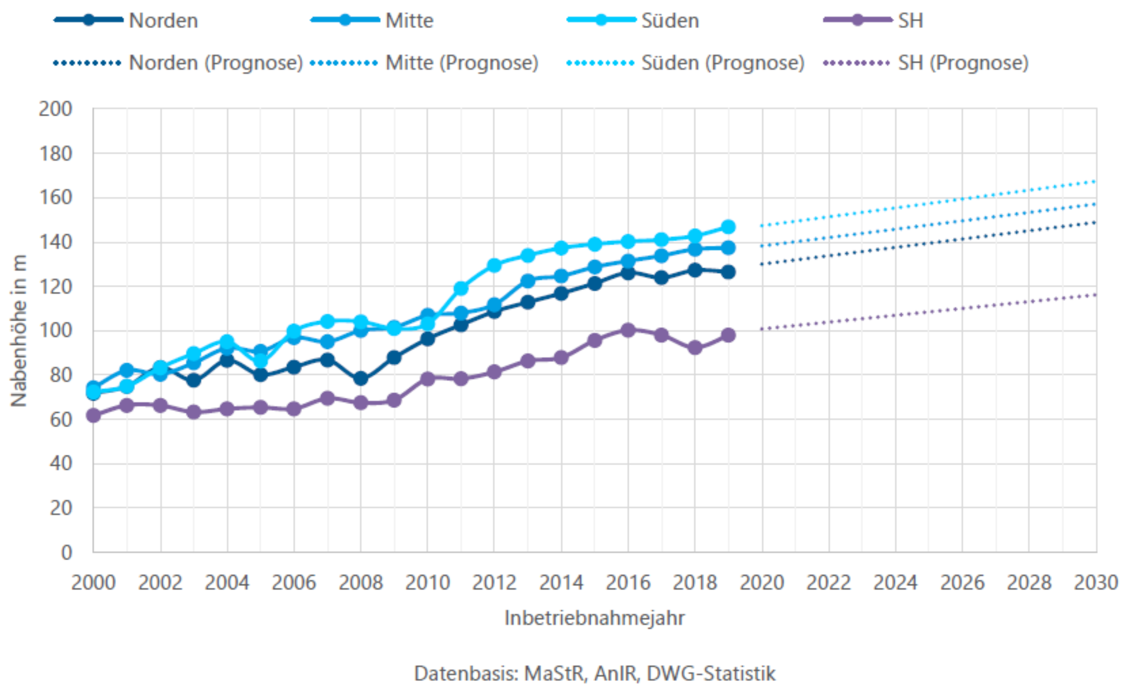

Figure 11: Development and forecast of mean hub hight (in m) for WTs installed in Germany. Figure taken from Deutsche WindGuard 2020 [53].

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 10). 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 12. 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 [53].

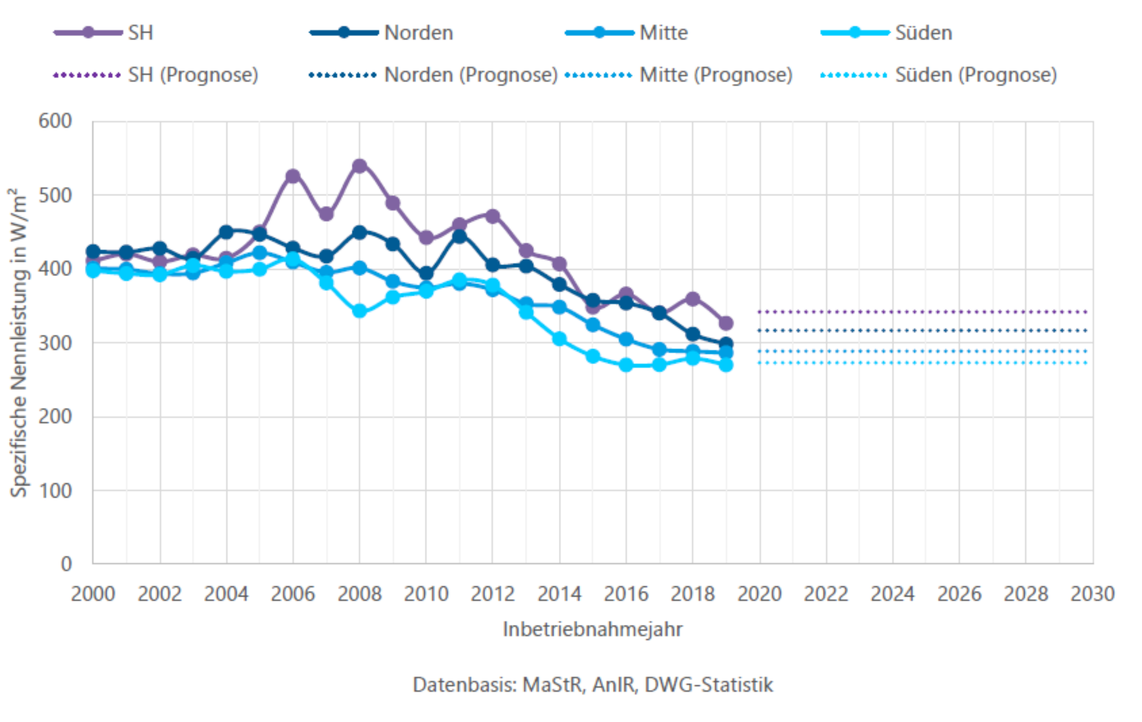

Figure 12: Development and forecast of the mean specific rated capacity (in W/m²) for WTs installed in Germany. Figure taken from Deutsche WindGuard 2020 [53].

2.9 Résumé

This section will briefly summarize the main points that have been presented regarding the main trends of development that are important for onshore WTs and are related to the calculations and findings of this thesis. 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 [33]. 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. In order to calculate the wind energy potential specifically for RLP in the context of climate change as described earlier, the methodology used in this thesis is partly adopted from the study of the DWG. Modern data processing with R is used to estimate the electricity yield of future WTs in RLP. The following chapter therefore describes the methodology developed for the analysis of the master and movement data from Amprion of 2012-2019. Additionally the area consumption of WTs in RLP is being assessed using the market master data register.

3 Materials and Methodology

3.1 Reproducable research and data science with R

Reproducibility or reproducible research is a major principle of reliable scientific methodology and is becoming increasingly popular and common practice with advancing computer technology, open source programming languages and fast self-developed statistical analysis. For the findings of a study to be found reproducible means that results obtained by an experiment or an observational study or in a statistical analysis of a data set should be achieved again with a high degree of reliability when the study is replicated. For the preparation and the analysis of the data included in this thesis, "R" which is an open source programming 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 [54]. Extensions of the actual language are called packages of those the following are in use: 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 [55]. All the data preparation, filtering, merging and formatting in this work was performed using base R or dplyr.

For the purpose of education and reproducibility, which are prerequisites for this study, the whole work was written with the programming language R. To be more precise the statistical analysis was done in R and the thesis itself was written in R Markdown. In essence R Markdown stands on the shoulders of knitr, which is an R package and translates all sorts of code, mainly the R code itself into markdown code [56]. Pandoc, which is a free and open-source document converter, then translates this code into an output format such as HTML, PDF or Word. In this case the R Markdown code is translated first into a LaTeX form which then is further transferred into a PDF output. Markdown itself is a markup language that is widely used in blogging, instant messaging, online forums and readme files. LaTeX on the other hand is a software system that is used for document preparation and is also sometimes referred to as literate programming because the user types plain text and code elements for specifying the formatting of the document in contrast to the "what you see is what you get" and drag and drop principle of word processors like Microsoft Word or Libre Office [57]. The formatting and layout of this master thesis comes from a package of the Humboldt-University of Berlin (HU) which offers a template for a thesis according to the regulations of HU. This package is related to the bookdown package, which is a template structure for writing books, ebooks, manuscripts, HTML documents and more. Due to exhaustive code only the line chart outputs are shown in this work as well as some important pieces of code in the appendix. The full documentation, especially the preparation steps can be found on `https://github.com/EliasCuadra/master-thesis-repowering` with explanatory README.md files that contain descriptions of variables and processing steps. Git, which is a version control software, was used initially to create several versions of the same chunk of code and ultimately to create a backup in the cloud. When this work is to be completely comprehended and reproduced or the methodology should be applied in another context or is to be adopted in another state it is definitely recommended to look into the GitHub folder since at least half of the time for this work was actually spent creating all the code and files needed for the analysis, which is not necessarily reflected in the written thesis.

3.2 Regression analysis

A regression analysis is used to check whether there is a relationship between the values of two or more variables and how strong this relation is. In the context of the data evaluation of the amount of electricity fed into the grid from WTs, the amount of electricity, the installed nominal power and the energy density depending on the commissioning date are of particular interest in order to be able to make statements about future developments. This relationship is tested in a regression analysis in the form of a comparison that measures the change in the dependent variable when the value of the independent variable increases or decreases by the value 1. Since this study uses only a very simple statistical analysis, only a simple linear regression with two variables is used, which in some cases is supplemented by a third-order polynomial equation to simulate disproportionate growth. The procedure is that from the data points, in this case the electricity yield or rated capacity per WT in relation to the commissioning date, that linear function equation is selected which makes the sum of the squares of the deviations, also referred to as the residuals, from the data points to this exact line is as small as possible. This is also why linear regression is also called *least-squares estimation* [58]. A simple overview about a chart that shows a linear regression output with explanations is show in Figure 13.

To explain some fundamentals, the variance in statistics is the expectation of the squared deviation of a random variable from its population mean or sample mean. Variance is therefore a measure of dispersion, meaning it is a measure of how far a set of numbers is spread out from their average value. The R-squared (R^2) value in this context is the proportion by which the variance of the dependent variable is explained by the variance of the independent variable. This should not be mistaken for the strength of the overall relationship which would be the correlation. For example if R^2 is 0.5 this means

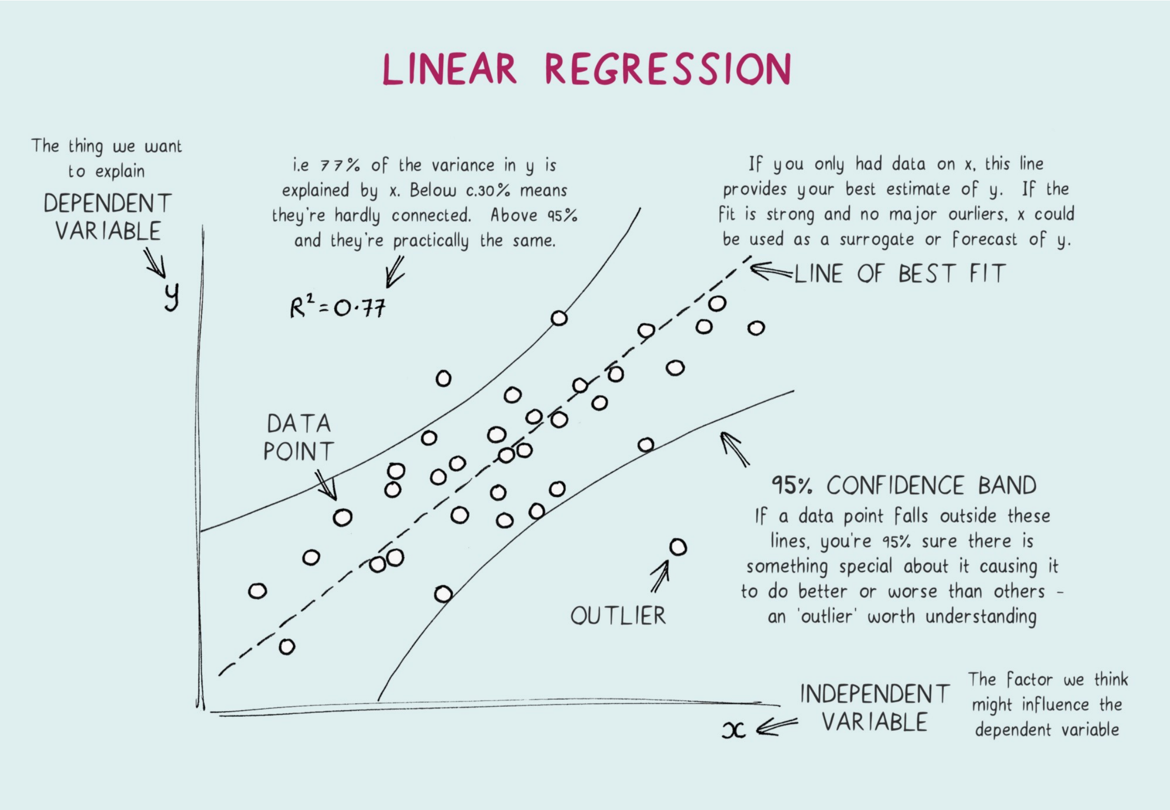

Figure 13: Basic representation of linear regression analysis with date points, regression line and confidence intervals (Figure from towards data science [59]).

that 50% of the variation in the data can be explained by the variation of the input data. The results in Chapter 4 are also presented with a p-value. The p-value is the probability that random chance created the results that were observed or something that is even more extreme and is therefore a measure of the statistical significance. The lower the p-value the greater the significance [60]. To find outliers and clean the data Cook's distance is used in this work which is a commonly used estimate of the influence of a data point when performing a regression analysis. All the statistical methods are carried out with the R programming language and all outputs and diagnostic plots did not show any critical structures within the data. Further explanation of statistical procedures is therefore avoided and also regarded as common sense. In the following example code it is shown how a linear model of the electricity yield in MWh as *menge_mwh* over the commissioning date as *inbetriebnahme* from the amprion data set is created using the lm() function, subsequently the summary function is called to see the significance and the R^2 value of the model and finally the diagnostic plots of the model are printed to check the model assumptions of a linear regression model such as normal distribution, independence of error, homogeneity of the variance and that no outliers are detected with Cook's distance (Figure 14).

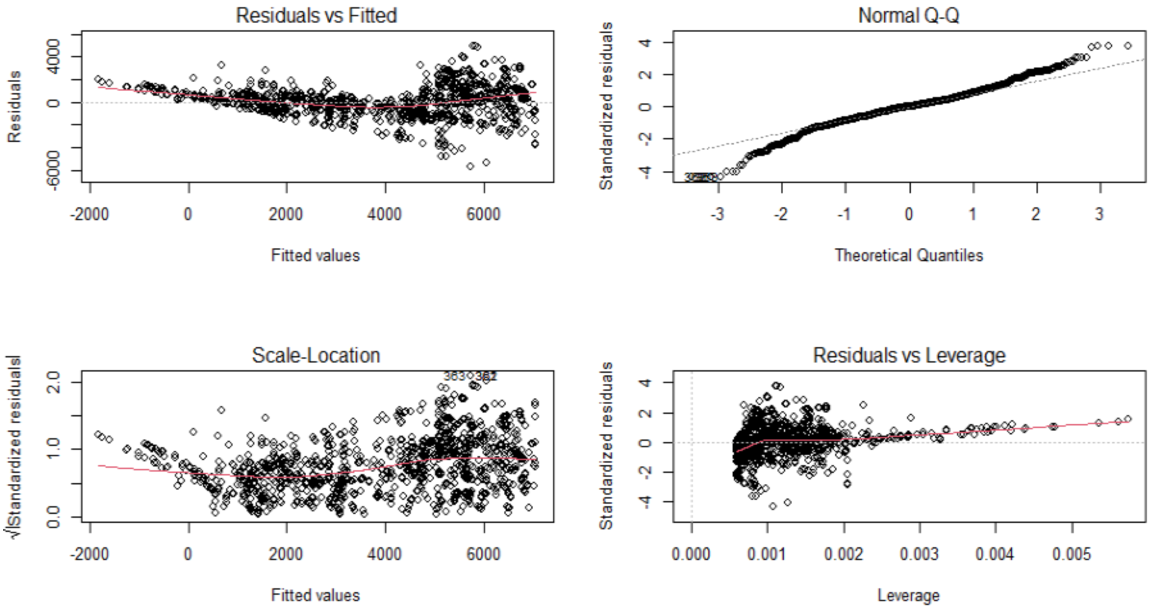

Figure 14: Example diagnostic plot of linear model of the electricity yield of all WTs in RLP over the commissioning date in 2019 from the transmition system operator Amprion created with the plot() function

The residual vs fitted values plot in the upper left reveals if the residuals are equally distributed among the outcome variables or have a non-linear pattern. In this case the residuals become larger with increasing fitted values which indicates an increasing error. The normal QQ plot in the upper right shows that the data is normally distributed if the dots follow the straight line. In this case the values stray from the straight line when becoming very small or very high which means the normal distribution is disturbed towards extreme values. The scale-location plot in the lower left similar to the first plot shows whether the assumption of equal variance (homoscedasticity) is matched if there is a straight line with equally spread points. The residuals vs leverage plot in the lower right helps to find influential points. When points are outside Cook's distance, usually indicated by a red dotted line which is not visible in this example, they are considered to be influential and can be removed from the data, although every case and data set has to be judged individually [61].

3.3 Geospatial analysis and area calculation with R

For the estimation of the distance between WTs in RLP and the subsequent calculation of the area consumption, a short geospatial analysis of the data was carried out. The data contained geographic references in a spherical coordinate system using longitude and latitude values called World Geodic System 1984 (WGS84). A Geographic Reference System (GEOREF) or coordinate reference system

(CRS) is a geocode or coordinate-based local, regional or global system used to locate geographical entities or specifying locations on the surface of the earth [62]. To perform the analysis the R packages sp, sf, spatstats, rgeos and rgdal were used. In particular or as a central operation the nndist() function was used to calculate the nearest neighbor of each WT. R was selected to be used for this and all other purposes in this work because it provides freely accessible packages, e.g., for spatial analysis that provide all the necessary tools for checking, manipulating and analyzing data [63].

3.4 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 [9]. 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 [13]. 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. Since it is considered best practice to examine the data for influential points and reliability this is also thoroughly done here [64]. For the prediction of the electricity yield not all the WTs are considered meaningful and some outliers are removed from the data. On the one hand WTs with a rated capacity lower than 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 15, 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.

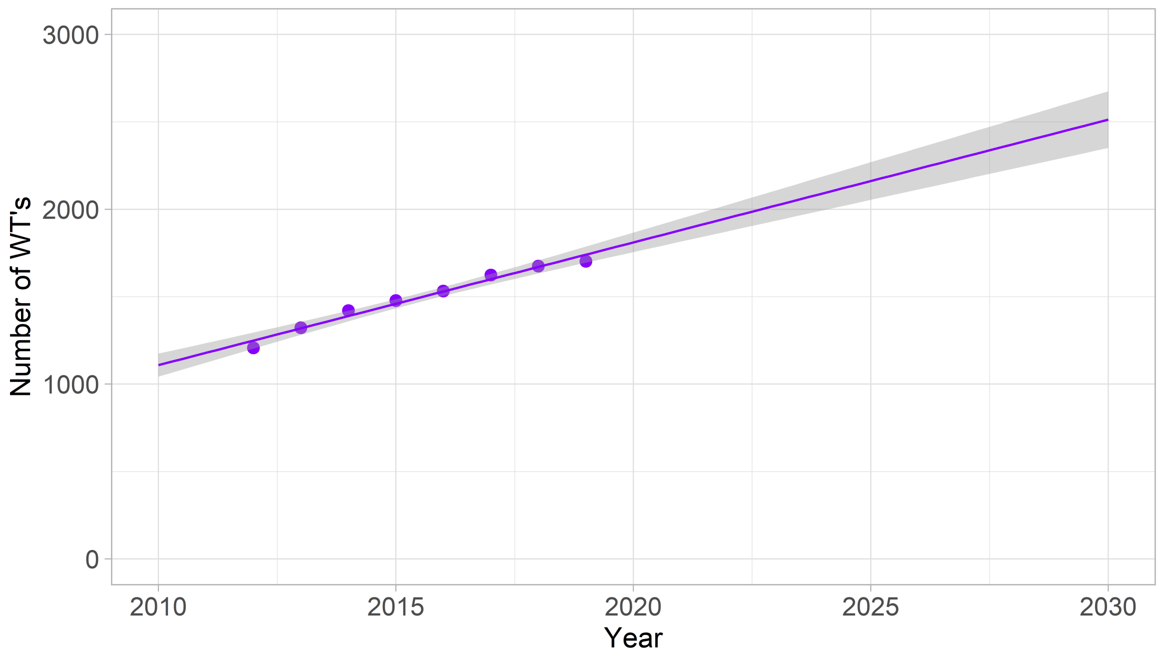

Figure 15: Number of total WTs in RLP from 2012 to 2019 according to Amprion with linear trend up to 2030

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, resulting from the division of electricity yield by 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 16. 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. 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. 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 since polynomial models did not create a better fit and sometimes even a decrease for the future. Additionally 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. The Code that was used to perform the analysis can be found in the appendix as A.1 Code chunk 1.

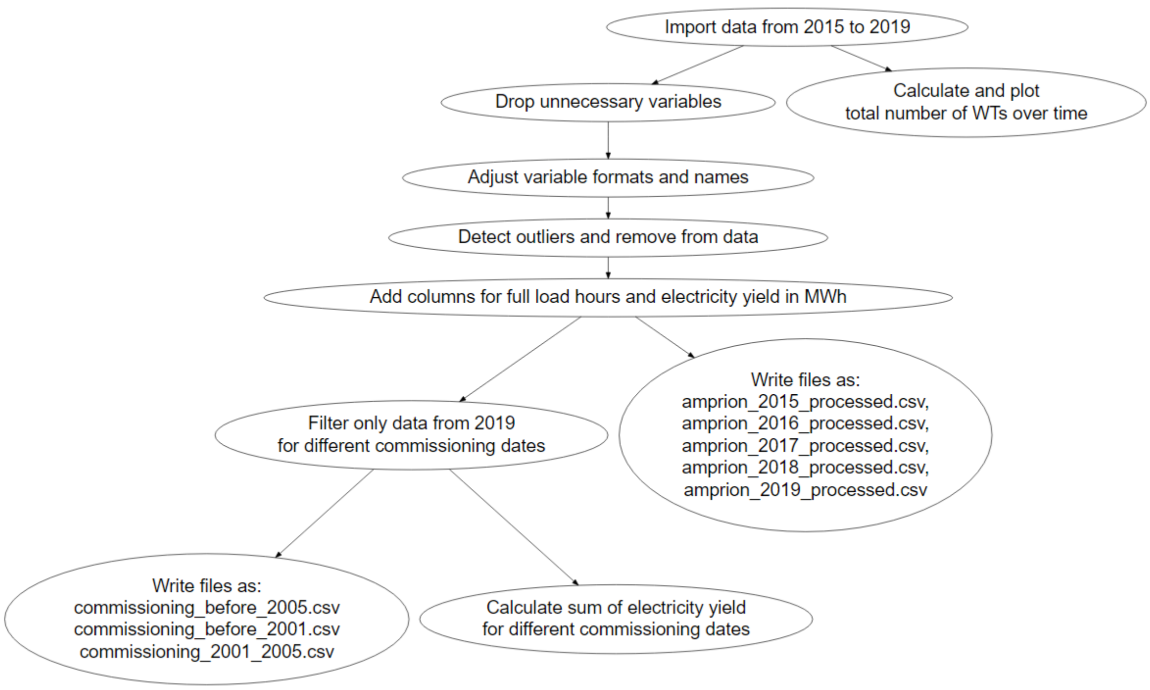

Figure 16: Flow chart of the cleaning and proccessing steps of the data from Amprion

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 data set and the respective process is described in the next subsection.

3.5 Data from the market master data register

The market master data register (Marktstammdatenregister - MaStR) contains data about all electricity and gas power generation units and can be freely accessed here:

https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/ OeffentlicheEinheitenuebersicht

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 17. The R code is stored as MaStR_amprion.R in the MaStR_amprion folder.

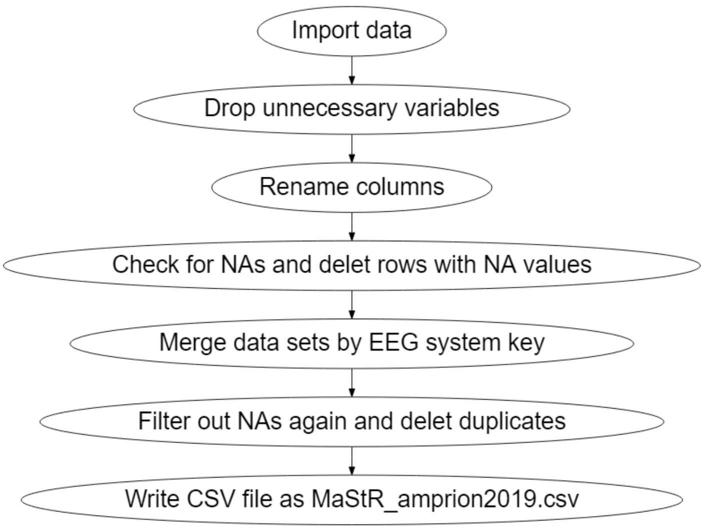

Figure 17: Flow chart of merging process of the data set from Amprion of 2019 and the data from the MaStR

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. After cleaning the data from WTs that were probably incorrectly located outside of RLP 1,589 WTs remained. For the analysis of the development of the rotor diameter, hub height and area consumption a nearest neighbor analysis is performed to find the distance between WTs. The Code that is used to do the geospatial distance estimation is shown in the appendix as A.2 Code chunk 2. A flow chart that shows the processing steps is shown in Figure 18. From knowing the distance to the nearest neighboring WT the area occupied by the WT is calculated as the square of that distance d^2 being the area covered by a rectangle around the WT. This also takes into account that the area that must be shown in plans and maps are usually greater than the actual occupied area which might be more accurate by calculating a circle around the WT. The electricity yield over the area consumption then reveals the energy density in kWh/m². Further, the data is cleaned from data points with no value for the electricity yield available as well as outliers. For example rotor diameters as well as hub heights over 200 m are considered unrealistically high for the calculation of a average value. For the area consumption it is assumed that if the distance to the next WT is greater than 1,000 m it is not because of shadowing effects. Also when the value is 0 it is deleted from the data. WTs with a electricity yield of less than 20 MWh and a distance of less than 30 m are also deleted. Also an energy density of more than 500 kWh/m² is regarded as too high. Similarly to the procedure that was performed to the data from Amprion and described above, a regression analysis to find a prediction for the area consumption if 22 TWh should come from wind energy in the year of 2030 is done. Respectively the Code can be found in the appendix as A.3 Code chunk 3. In this chapter it was described how reproducible research and data science with R was used to create a robust and reproducible methodology for analyzing data from the transmission system operators and the MaStR to create an assessment about the potential of wind energy within a certain area. Furthermore it was explained how geospatial analysis was used to estimate the area consumption of the existing WTs in RLP with detailed description of the two data sets that were used. The next chapter will describe the results that could be extracted from the analysis.

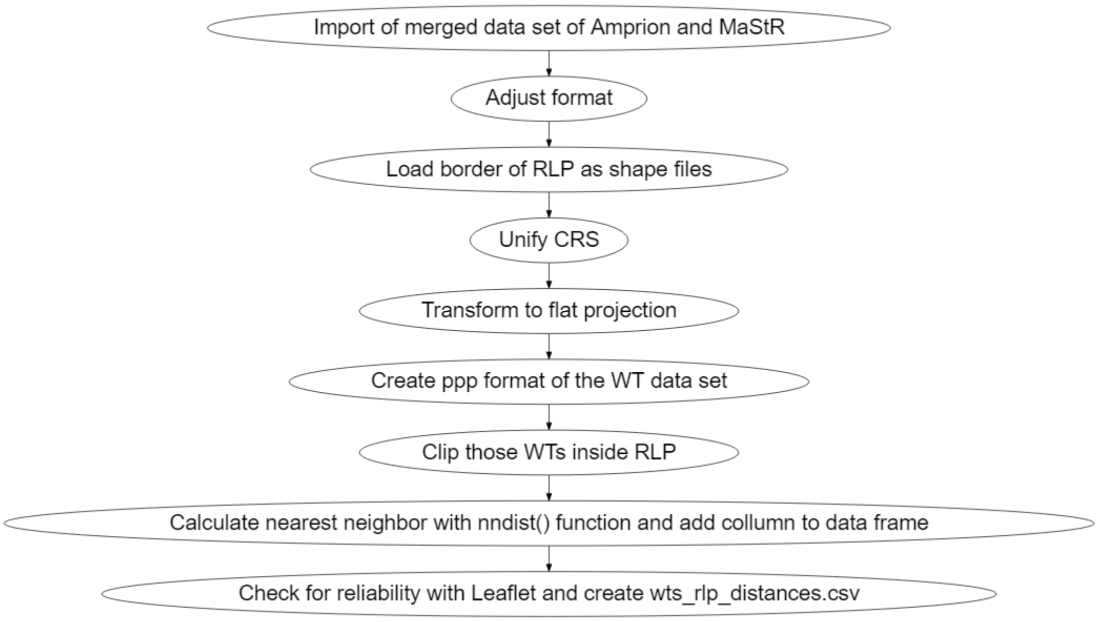

Figure 18: Flow chart of the geospatial processing

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. The residual vs fitted values plot show that the residuals become greater with increasing values 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, as presented in Figure 14, shows that the residuals of average values are largely normally distributed in this model. 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, unpredictable wind conditions in some locations or very small systems with other requirements. 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. This must be like that since it was already indicated in the residuals vs fitted values plot. The residuals vs leverage plot shows that none of the observations have a large Cook's distance and therefore there are no influential outliers. The plot with all models of the electricity yield over the commissioning date as a main result is shown in Figure 19.

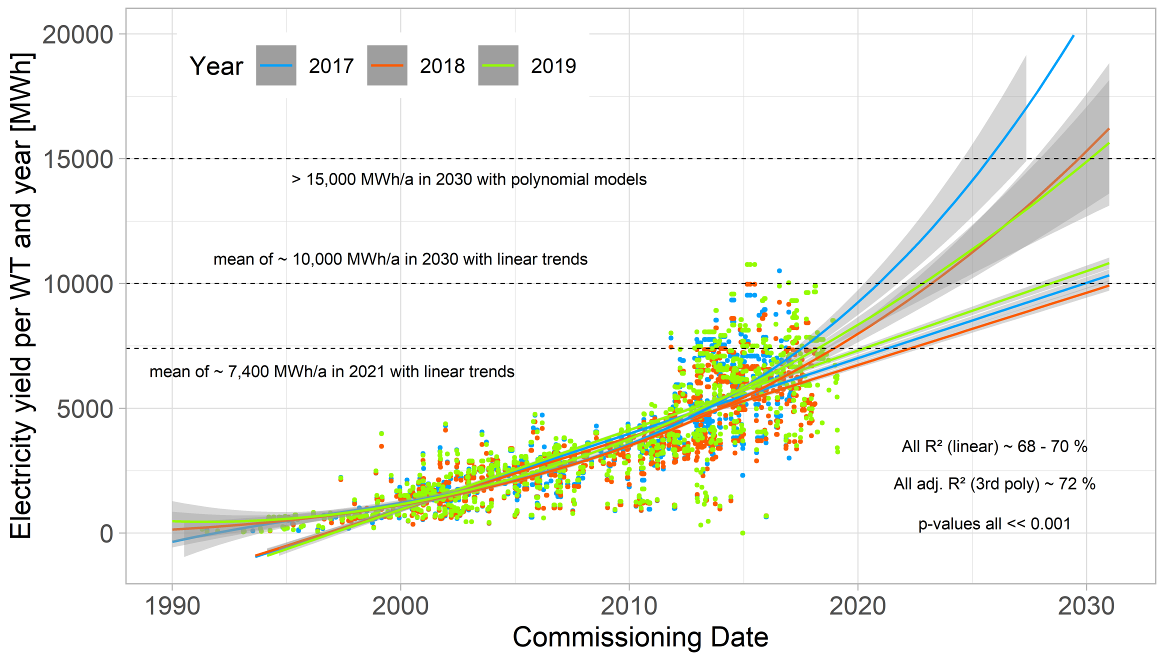

Figure 19: Development and forecast of electricity yield in Rhineland-Palatinate using data from 2017 to 2019 with linear trends and 3rd order polynomial models

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 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/a per WT on average in the year 2030 seem relatively high and the assumption of 10,000 MWh per WT of the linear trends is more reasonable. However, the DWG forecast in Figure 9 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. Additionally, as presented in chapter 2.3, the WT manufacturers give reason to believe that the electricity output per year will increase to 15,000 - 20,000 MWh/a with an average wind speed of 6 m/s within the next years. Hence, the prediction of 15,000 MWh on average in 2030 is not outside of the possible, considering a rapid expansion of WTs. For the following plots and 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 20.

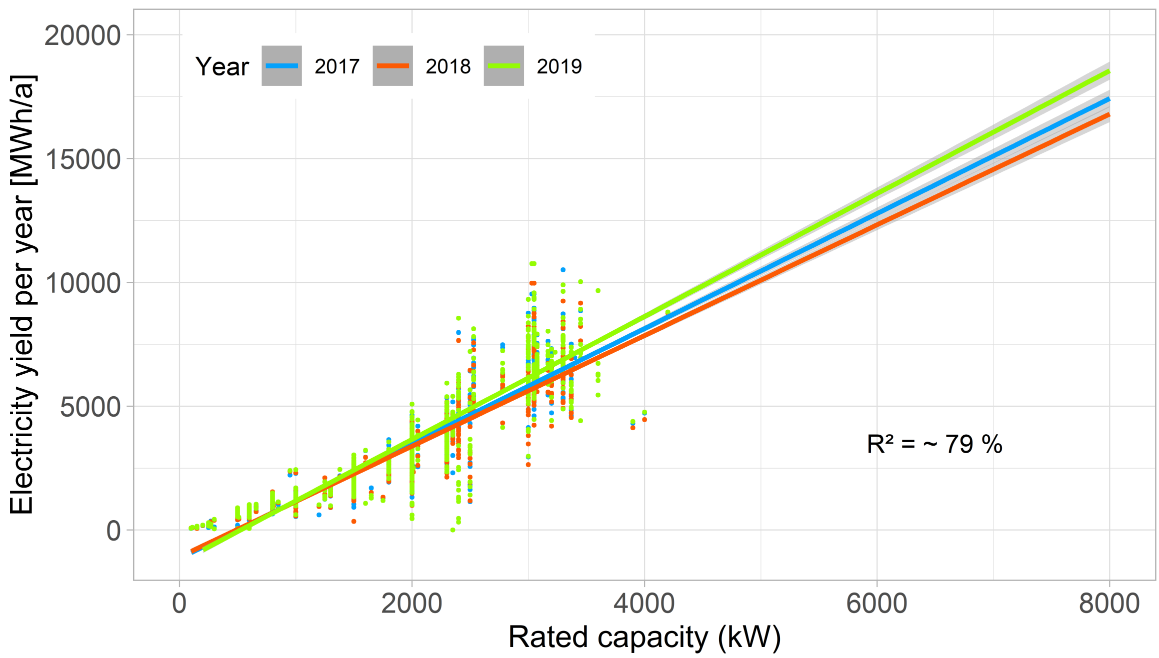

Figure 20: Electricity yield over rated capacity in RLP with data from 2017 to 2019

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. Also do those linear trends capture the predicted 15,000 MWh/a electricity yield of the V162-5.6 IEC S with a rated capacity of 5,600 kW given that the wind speed in RLP is a little lower as in the data sheet of the manufacturer. Noticeable is the steeper increase in 2017 over the year 2018 which suggests different annual wind conditions that might influence this trend significantly. But not only the overall electricity yield increases also the variance increases. 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 10,000 MWh/a that were presented before, turbines with an average rated capacity of 5 MW seem to be required. The plot of the rated capacity over the commissioning date with data from 2019 is shown in Figure 21. 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. Using a polynomial trend does not further improve or change this result. 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, the average generator size of 3.5 MW for the current moment can be used for calculations.

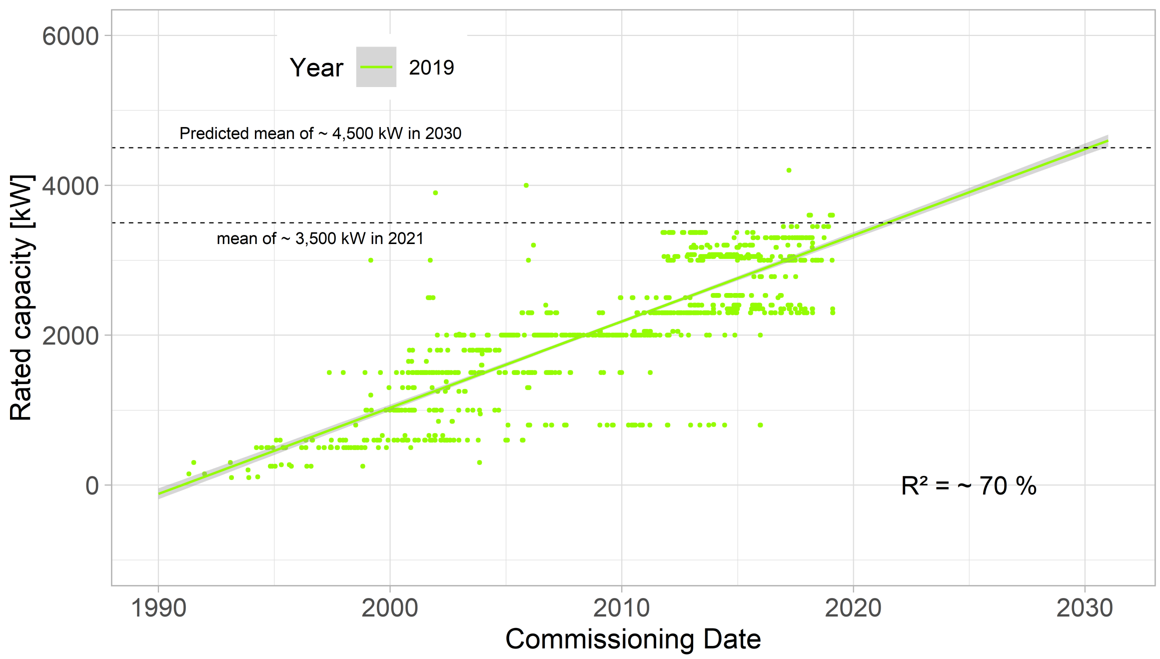

Figure 21: Rated capacity over commissioning date

The next plot shows the full-load-hours over the commissioning date in Figure 22. 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 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 but it also shows that the difference is within a small range and does not influence the overall perspective of ten years. The mean of all models for 2021 is around 2,300 h/a and is therefore recommended for further calculation.

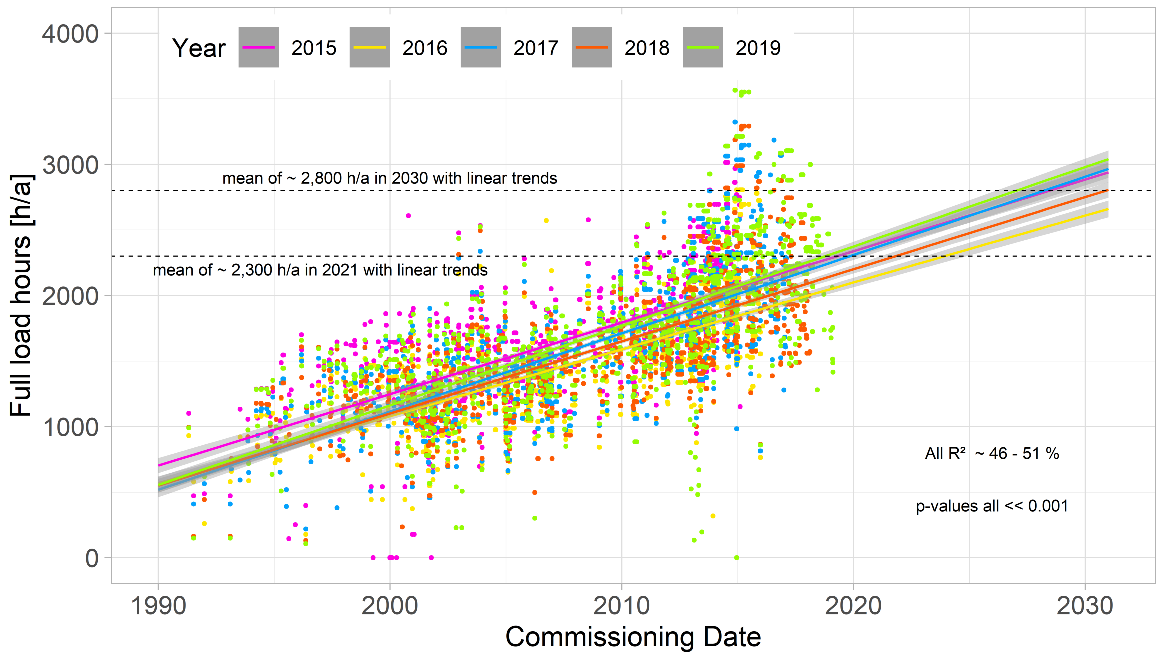

Figure 22: Full-load-hours over the commissioning date using data from 2015 - 2019

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/a. 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 that calculating 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 the full-load-hours reveal a load factor of around 26%, which is much more than the mentioned 19% from the literature [46] 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 of 2,300 by the average rated capacity for 2021 of 3.5 MW 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. It is important to mention that this development toward increasing electricity yield of one WT 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 larger WTs and also to harvest higher wind speeds at greater altitudes, the overall energy extraction per area has certain limits that cannot be exceeded. Therefore the calculations of the respective area consumption are presented in subsections 4.3. Before that the repowering potential is investigated next.

4.2 Repowering potential

The WTs in RLP that are potentially suitable for repowering within the next 10 years are systems with commissioning date before 2006. If possible this means a total replacement of 514 WTs with a total electricity output of 841 GWh. If we assume, by looking into chapter 4.1 and Figure 19, that the average electricity yield of a newly commissioned WT within the next 10 years can be 12,500 MWh on average the combined electricity yield of 514 WTs of that kind would be 6,425 GWh or roughly 6.4 TWh which is well above seven times more than before. Further, the 514 WTs have been arbitrarily divided into two categories in order to see the influence of the commissioning date (Table 2). Additionally an interactive map that shows exactly how high the potential for each individual WT is in RLP was created and cannot be shown here but is to be found in this project under data/MaStR_amprion_analysis/repowering_map as repowering.html.

Commission	Number of WTs	Electricity yield [GWh]	Potential [GWh]	Increase [%]
before 2001	186	186	2325	1250
2001 to 2005	328	655	4100	625

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

It is highly questionable, if all of the old systems can be replaced due to distance regulations and approval procedures because larger WTs might have an accordingly larger area consumption due to larger rotor diameter. On the contrary, it could also be possible that the areas in which old systems are already installed due to good wind conditions are chosen for further harvesting of the winds energy. Hence, more WTs will be built in those places. Admittedly, these considerations are beyond the scope of this thesis. Additionally, I want to argue that the term repowering in this context is misleading. It suggests that a system is technically enhanced, although it means the deconstruction of an old systems and new construction of another system, which might even be in a different location. This is also why 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 critical. Hence, the calculation of the area consumption follows next.

4.3 Rotor diameter, hub height and area consumption

The analysis of the merged data from Amprion and the MaStR revealed an average rotor diameter of around 86.5 m and about 110 m hub height on average. The plots of the rotor diameter and hub height over time with a linear trend up to 2030 is shown in Figure 23.

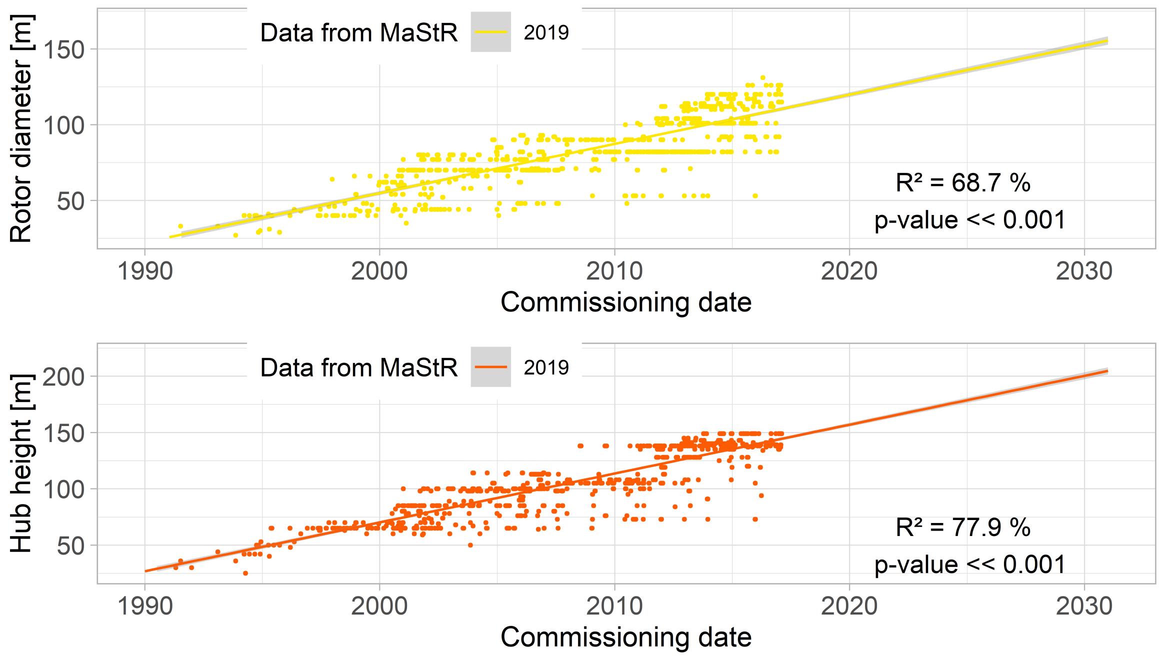

Figure 23: Rotor diameter and hub height of WTs in RLP over the commissioning date from 1990 to 2019 with linear trend to the year 2030

A steady increase can be seen as the reasons for that have already been explained and the expected average rotor diameter in 2030 is about 150 m and the average hub height around 200 m. As described before these kind of sizes are already been offered by the big manufacturing companies. For the purpose of analyzing the electricity density, data points that would distort the results are taken away from the initial 1,589 WTs and 1,216 remained. Figure 24 shows the plot of the electricity yield per m^2 which can be referred to as the electricity density per year over the commissioning date of the merged data set that originated from the MaStR and the master and movement data from Amprion of 2019. Although the model is highly significant only 11% of the variation in the dependent variable is explained by the commissioning date. Therefore and because almost 400 WTs had to be taken out of the data set because of missing or unrealistic numbers the overall prediction power of the model is low.

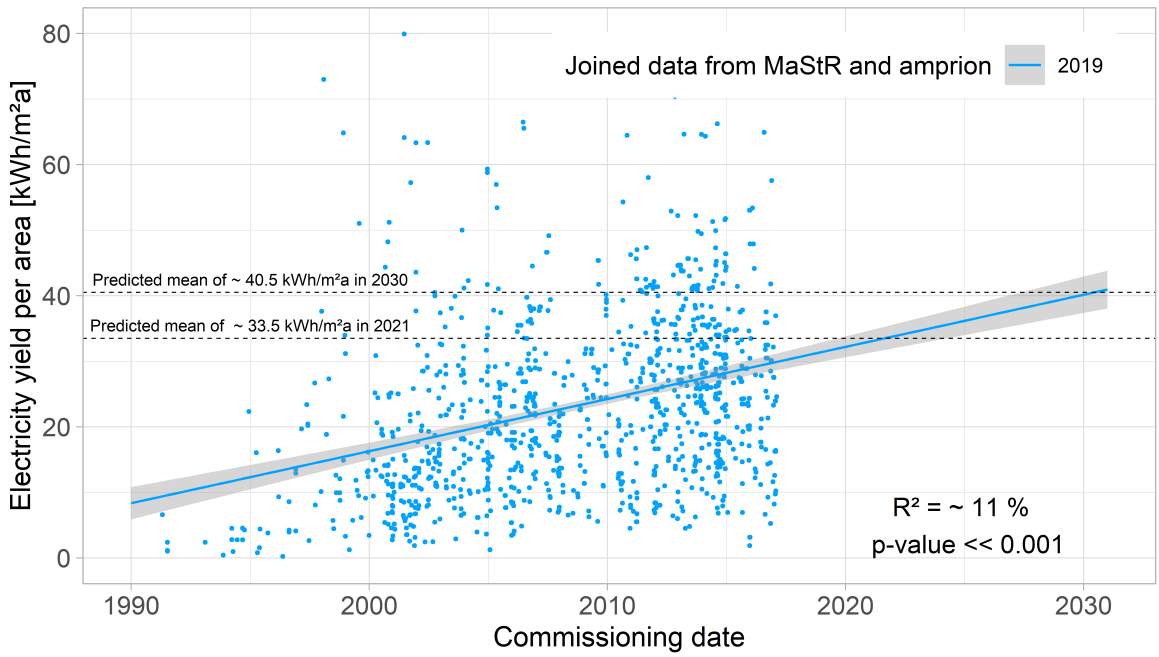

Figure 24: Electricity density in kWh/ m² and year over the commissioning date

Nonetheless, the average distance to the nearest WT of all WTs is a reasonable 412 m which equals to an area consumption per WT of about 169,744 m^2 or roughly 0.17 km^2. This means that the total area covered with currently 1,702 WTs is about 289.34 km^2, this equals to around 1.46% instead of the 1.8% that were theoretically derived in chapter 2.1 of the total area of RLP which is 19,858 km^2. This is either because the assumption of 6 m/s is actually wrong and the wind speed in RLP is higher or the distance between WTs is smaller than five times the rotor diameter. To reiterate, this area includes not only the site were the WT is located or the swept area of the rotor but already considers the distance around a WT in which no other WT can be built. With an electricity yield of 6.782 TWh in 2019 this means that the average electricity yield per area and year equals to around 23,44 kWh/m^2a which is a constant power output of about 2.675 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 6.35 m/s to reach a power output of about 2.61 W/m^2 and a distance to the next WT of 5 times the rotor diameter. Hence, this is definitely an indicator for the utilization of higher wind speeds in greater altitude with the technical development towards greater hub heights. Furhtermore, it means that the value of five times the rotor diameter is too high for newly commissioned systems and therefore changes the proportions. The increase in rotor diameter alone 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 [46].

Due to the constant technical development it makes sense to take 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 467 m, but decreases in relation to the rotor diameter to 4.6 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 238,527 m^2 which is 0.243 km^2. The average electricity yield is about 30.5 kWh/m^2 which relates to a constant power output of 3.47 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. Vice versa this means that if the distance between WTs can be reduced, the overall wind speed to generate this electricity density decrease significantly, which means a smaller area consumption. 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 the project development companies and the manufacturers a distance to the neighboring WT can be reduced to 3 times the rotor diameter. If we look at a Vestas V162-5.6 IEC S with a rotor diameter of 162 m which relates to an area consumption of around 236,196 m^2 according to the previous assumption the expected electricity yield at 6 m/s is around 15,000 MWh.

This means the electricity density is about 63.5 kWh/m^2 per year which relates to a constant power output of around 7.2 W/m^2. This also means that the 40.5 kWh/m^2 on average presented in Figure 24 for the year 2030 could be realistic. According to the presented numbers three possible scenarios using the mean predicted for 2021 and 2030 as well as the calculation from the Vestas WT as well as the required wind speed to generate that electricity density and the respective area consumption if the goal of 22 TWh should be reached in 2030 are shown in Table 3. It must be mentioned that for the calculation of the required wind speed it is assumed that the distance of 3 times the rotor diameter that was used to calculate the electricity density of a new Vestas WT was also used for the other scenarios. Additionally, the value for 5 times the rotor diameter is also put into the table to show the significant difference that the distance to the next WT has.

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] with 3d	Req. av. wind speed [m/s] with 5d
Mean 2021	**33.5**	**3.8**	**657**	**3.3**	**4.4**	**7.1**
Mean 2030	**40.5**	**4.6**	**543**	**2.7**	**4.7**	**7.6**
Vestas	**63.5**	**7.2**	**347**	**1.75**	**5.5**	**8.8**

Table 3: Three scenarios of electricity yield per area and year and their respective area consumption and theoretically required (Req.) average (av.) wind speed once for a distance between the WT of 5 times the diameter (5d) and once with 3 times the diameter (3d), if a consumption of 22 TWh should be generated with WTs in 2030. Mean 2021 and Mean 2030 were taken from the linear regression model shown in Figure 24 and the Vestas scenario is as described in the text with the V162-5.6 IEC S machine.

5 Discussion

This thesis has already presented the state of the art, methodology, calculations and analysis, and in this chapter the results will be critically discussed and placed in a wider context. At the beginning of this thesis it was shown that the topic of the energy transition and in particular the development of wind power onshore is given high social relevance as well as importance in terms of security of supply [65]. It was shown that roughly 22 TWh of electricity must come from the winds power of RLP, if the climate protection targets of 2030 must be achieved. In this sense and against the background of the German federal election in September 2021 and the ongoing trend-setting coalition negotiations, the energy transition will be visibly highlighted. This state of focus on the current development and imminent transformation of the energy systems is of course not a German phenomenon, but rather preoccupies the European Union as well as all communities in the whole world. Due to the consequences of climate change and changes in the environment and supply systems, certain regions are being affected more than others. In this sense the research and development of renewable energy systems is more topical than ever. Renowned institutions such as the Fraunhofer Society, the Institute for Climate Impact Research and many universities, organizations and businesses deal in detail with the question of how exactly this transformation can succeed. One answer to this question seems to be clear: the capacity of onshore wind power will be further expanded! This is reflected in the development trends of Deutsche WindGuard shown in Chapter 2 and the other reports presented on the technical development of wind power. However, there are certain limits to wind power on land. The availability of suitable locations is limited by the amount of wind, nature conservation issues and of course by the acceptance of the citizens [66]. For this reason, a potential analysis, as in this case for Rhineland-Palatinate, which must then be compared with the climate protection goals to be achieved, is logical. In this master's thesis, based on the feed-in data from the transmission system operator Amprion and the data from the MaStR, a relatively technical but robust analysis of the expected feed-in quantities and the expansion rate as well as the area requirements was made.

In order to answer the first research question about the potential electricity yield of newly commissioned WTs between 2021 and 2030 it can be stated that the expected amount of electricity that can be fed-in by a wind power plant will rise steadily and is already determined in technical data sheet to be around 15,000 MWh at an average wind speed of 6 m/s, depending on the manufacturer's information [33]. According to the modeling done for this study, there is an average feed-in quantity over all WTs of a minimum of 7,400 MWh in 2021 and about 10,000 MWh in 2030, assuming a linear increase. With an exponential increase, the quantities could even reach 10,000 MWh in 2021 and over 15,000

MWh in 2030. It is therefore difficult to reliably determine a specific value here, since the speed of expansion is strongly related to political decisions.

The second research question about the repowering potential can be answered in saying that the total number of repowering plants, i.e. plants with a commissioning date before 2006, is 514 with a total feed-in quantity of 841 GWh. If all of these systems were to be replaced with an output of 12,500 MWh, there would be a potential increase of 5584 GWh additionally.

The answering of the third and most important question about the area consumption is done by seing that thhe total number of wind turbines will continue to increase in RLP and the expected number of 2,500 will be reached in 2030 if the expansion rate remains the same. Similarly the rotor diameters will increase to more than 160 m which means the total height of WTs will increase up to 250 m and more. Further it could be shown that the predicted electricity density for 2030 for RLP is 40.5 kWh/m^2 and relates to a constant power output of 4.6 W/m^2. With this predicted power density, the amount of area required to cover the demand of 22 TWh in 2030 would be roughly 2.7% of the total area of RLP. As the state of the art of the manufacturers show the output for newly commissioned WTs will definitely increase to above 60 kWh/m^2 within the next five years. Due to fast expansion the electricity density could therefore increase up to an average of 63.5 kWh/m^2 in 2030 which relates to a constant power output of 7.2 W/m^2. With this higher predicted power density, the amount of area required to cover the demand of 22 TWh in 2030 would be roughly 1.75% of the total area of RLP. Thus, it can be concluded that, as a final and main result, the targets presented by the government can indeed be reached with a specific, fast and unbureaucratic expansion of WTs until they cover around 2% of the state.

Due to the high reliability of the publicly available data and the correspondence with the most recent and largest German DWG study, these results is very reliable. However, the criticism here is that the expansion of wind power or an individual system or an entire wind farm cannot be viewed in an idealized manner, but always depends on legal and social regulators and thus eludes a specific scientific analysis. Nonetheless, the results were also confirmed based on personal training and work at a project development company. For their conservative profitability calculations, for example in Baden-Württemberg, project development companies expect yields of 13,000 - 15,000 MWh at wind speeds of around 6 m/s or even a bit below that for a Nordex N163-5.X wind turbine with commissioning in 2026. A study by Jäger et al. from 2016 estimated the technical potential in Baden-Württemberg which is the neighboring state between 11.8 and 29.1 TWh but argues that this might not be feasible [67]. If only an average electricity generation of 7,400 MWh/a per WT is assumed, the number of

WTs needed to generate the demanded 22 TWh is around 2,973 WTs. If on average 8,050 MWh/a could be harvested then this would require around 2,733 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 very realistic. If the 22 TWh shall be generated with 2,500 WTs the average annual output must be 8,800 MWh, which also seems quite realistic because the numbers presented before are conservative and only estimates for the year 2021 and will certainly increase over the next ten years. Of course, WTs with lower total electricity yield would have to be repowered additionally to increase the mean output and effort has to be made to push ahead with the expansion of WTs in RLP, but it shows that it is certainly not out of the scope. On the contrary to the technical potential, 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 [30]. 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 that slows down the whole process [68]. From the results can also be seen that the power output per area can even exceed the value of 7 W/m^2 described by Linow [52]. It also demonstrates how the required wind speed is significantly lower to generate a higher electricity density when reducing the distance of WTs to each other. In the best case and not an unrealistic scenario it can therefore be seen that it might be reasonable to believe that the electricity demand of 22 TWh can be generated in the year 2030 with an average wind speed of 6 m/s by covering only 1.7% of the country with WTs. If compared with the occurrence of this wind speed shown in Figure 2 at 140 m above ground, it seems very reasonable to believe that with a hub height of more than 160 m the average wind speed will increase and therefore the electricity yield of covering the mentioned 2% of the country can even generate more electricity.

All this means that RLP meets the expansion targets in the area of wind power and the state's climate protection goals can also be achieved from a technical point of view. However, it should be noted that this analysis did not adequately address the regulatory and societal hurdles. In project development, for example, many areas cannot be used for wind power projects due to restrictions and community taboo criteria. The most important restrictions include sufficient distance from landscape and nature protection areas and endangered animal and plant species such as the red kite, black stork, sea eagle or certain bat and newt species as well as military areas, radars for aviation and radio relay routes, etc. These types of detailed analyses related to regulatory and societal restrictions are not the main focus of the work presented in this thesis, but are absolutely necessary in practice in order to implement wind power projects. However, this also eludes a specific quantitative analysis, as these restrictions are constantly changing and therefore cannot be clearly identified over a longer period of time.

6 Conclusion

The results of this work show that the expansion targets for electricity generation of 22 TWh from wind power in 2030 can indeed be achieved with 2,500 WTs and covering 2% of the state, which was already 2012 defined as a realistic number for the availabl area [69]. For this, a politically or socially controlled designation of areas is necessary. This is a concrete recommendation for action to the state government. Since the bigger hurdles in this process lie in nature conservation and in the resistance of the population, measures should be taken especially here. With regard to nature conservation, the main concern here is the creation of compensatory habitats and the use of mechanisms and techniques, such as the shutdown of systems in situations where animal species are endangered [70]. For this purpose, further research on the behaviour of the animals is recommended and it should be checked whether the endangerment of red list species can be minimized. Another very important topic is acceptance by the local people. In particular, it should be investigated how better participation and communication increases the acceptance, which is already at a high level, of such projects and reduces resistance [42]. The issues of noise pollution, the optically oppressive effect and the throwing of ice are also a constant cause of concern in wind power projects. A lot of energy is already invested in engineering research into noise reduction and rotor blade heating, and this is certainly recommended for the future and will be continuously developed.

It is therefore almost certain that the expansion of wind power in RLP will proceed at a similar speed or even accelerated, the expansion targets and thus also the targets for climate protection by 2030 will be achieved. However, this only applies explicitly to the assumed electricity demand of 33 TWh of which 22 TWh can come from wind power. However, it can be assumed that the electricity demand will continue to increase due to the electrification of mobility and heating and also for energy-intensive industries, above all BASF in Ludwigshafen with extremely energy-intensive processes such as steam cracking. Whether it is possible to run the entire economy of RLP based solely on its own wind and solar power remains questionable and must be investigated in further studies.

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A Appendix

A.1 Code chunk 1

```
##################################
#Statistical analysis of the data#
##################################

#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("results_of_preparation/amprion_2015_processed.csv")
amprion_2016 <- read.csv("results_of_preparation/amprion_2016_processed.csv")
amprion_2017 <- read.csv("results_of_preparation/amprion_2017_processed.csv")
amprion_2018 <- read.csv("results_of_preparation/amprion_2018_processed.csv")
amprion_2019 <- read.csv("results_of_preparation/amprion_2019_processed.csv")

#formatting commissioning date
amprion_2015$inbetriebnahme <- as.Date(amprion_2015$inbetriebnahme, "%Y-%m-%d")
amprion_2016$inbetriebnahme <- as.Date(amprion_2016$inbetriebnahme, "%Y-%m-%d")
amprion_2017$inbetriebnahme <- as.Date(amprion_2017$inbetriebnahme, "%Y-%m-%d")
amprion_2018$inbetriebnahme <- as.Date(amprion_2018$inbetriebnahme, "%Y-%m-%d")
amprion_2019$inbetriebnahme <- as.Date(amprion_2019$inbetriebnahme, "%Y-%m-%d")

#Linear model of electricity yield over commissioning date 2017 - 2019
#2017
lm_electricity_yield_2017 <- lm(
  amprion_2017$menge_mwh ~ amprion_2017$inbetriebnahme)
summary(lm_electricity_yield_2017)
plot(lm_electricity_yield_2017)
```

```r
#2018
lm_electricity_yield_2018 <- lm(
  amprion_2018$menge_mwh ~ amprion_2018$inbetriebnahme)
summary(lm_electricity_yield_2018)
plot(lm_electricity_yield_2018)

#2019
lm_electricity_yield_2019 <- lm(
  amprion_2019$menge_mwh ~ amprion_2019$inbetriebnahme)
summary(lm_electricity_yield_2019)
par(mfrow = c(2, 2))
plot(lm_electricity_yield_2019)

#check polynomial model
#2017
pm_electricity_yield_2017 <- lm(
  amprion_2017$menge_mwh ~
    poly(amprion_2017$inbetriebnahme, 3))
summary(pm_electricity_yield_2017)
plot(pm_electricity_yield_2017)

#2018
pm_electricity_yield_2018 <- lm(
  amprion_2018$menge_mwh ~
    poly(amprion_2018$inbetriebnahme, 3))
summary(pm_electricity_yield_2018)
plot(pm_electricity_yield_2018)

#2019
pm_electricity_yield_2019 <- lm(
  amprion_2019$menge_mwh ~
    poly(amprion_2019$inbetriebnahme, 3))
summary(pm_electricity_yield_2019)
```

```r
plot(pm_electricity_yield_2019)

#Plot the values with linear and polynomial trends for 2017 - 2019
pelectricity_yield_2019_poly <- ggplot() +
  geom_point(data = amprion_2017, aes(x=inbetriebnahme, y=menge_mwh),
             size = 0.4, colour = "#03a1fc") +
  geom_point(data = amprion_2018, aes(x=inbetriebnahme, y=menge_mwh),
             size = 0.4, colour = "#fc5a03") +
  geom_point(data = amprion_2019, aes(x=inbetriebnahme, y=menge_mwh),
             size = 0.4, colour = "#94fc03") +
  geom_smooth(data = amprion_2017,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2017"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2018,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2018"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2019,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2017,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2017"),
              method= "lm", formula = y ~ poly(x, 3),
              fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2018,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2018"),
              method= "lm", formula = y ~ poly(x, 3),
              fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2019,
              aes(x=inbetriebnahme, y=menge_mwh, colour = "2019"),
              method= "lm", formula = y ~ poly(x, 3),
              fullrange = TRUE, size = 0.5)  +
  theme_light() +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
```

```
  ylim(-1000, 20000) +
  xlab("Commissioning Date") +
  ylab("Electricity yield per WT and year [MWh]") +
  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") +
  geom_hline(yintercept = 7400, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("1997-01-01"),
           y=6500,label="mean of ~ 7,400 MWh/a in 2021 with linear trends",
           size = 2.5) +
  geom_hline(yintercept = 10000, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("2000-01-01"),
           y=11000,label="mean of ~ 10,000 MWh/a in 2030 with linear trends",
           size = 2.5) +
  geom_hline(yintercept = 15000, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("2003-01-01"),
           y=14200, label="> 15,000 MWh/a in 2030 with polynomial models",
           size = 2.5) +
  annotate(geom="text",x=as.Date("2026-01-01"),
           y=2000,label= "All adj. R² (3rd poly) ~ 72 %", size = 2.5) +
  annotate(geom="text",x=as.Date("2026-01-01"),
           y=3500,label= "All R² (linear) ~ 68 - 70 %", size = 2.5) +
  annotate(geom="text",x=as.Date("2026-01-01"),
           y=400,label="p-values all << 0.001", size = 2.5) +
  scale_colour_manual(name = "Year", values=c("#03a1fc", "#fc5a03", "#94fc03"))

#print plot
pelectricity_yield_2019_poly +  theme(legend.position = c(0.25,0.9))

#save plot as image
ggsave("results_of_analysis/electricity_yield_2017-2019.png",
```

```
       plot = last_plot(),
       dpi = 900,
       width = 7,
       height = 4)

#linear models with electricity over rated capacity 2019
lm_e_over_rated_capacity_2019 <- lm(
  amprion_2019$menge_mwh ~ amprion_2019$leistung)
summary(lm_e_over_rated_capacity_2019)
plot(lm_e_over_rated_capacity_2019)

#Plot electricity yield over rated capacity with linear trend 2017 - 2019
pe_over_ratedcapacity_2019 <- ggplot() +
  geom_point(data = amprion_2017, aes(x=leistung, y=menge_mwh),
             size = 0.4, colour = "#03a1fc") +
  geom_point(data = amprion_2018, aes(x=leistung, y=menge_mwh),
             size = 0.4, colour = "#fc5a03") +
  geom_point(data = amprion_2019, aes(x=leistung, y=menge_mwh),
             size = 0.4, colour = "#94fc03") +
  geom_smooth(data = amprion_2017,
              aes(x=leistung, y=menge_mwh, colour = "2017"),
              method=lm, se=TRUE, fullrange = TRUE)  +
  geom_smooth(data = amprion_2018,
              aes(x=leistung, y=menge_mwh, colour = "2018"),
              method=lm, se=TRUE, fullrange = TRUE)  +
  geom_smooth(data = amprion_2019,
              aes(x=leistung, y=menge_mwh, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE)  +
  theme_light() +
  ylim(-1000, 20000) +
  xlim(0,8000) +
  xlab("Rated capacity (kW)") +
  ylab("Electricity yield per year [MWh/a]") +
```

```r
  theme( axis.text=element_text(size=12),
         axis.title=element_text(size=13),
         plot.title = element_text(size=16),
         legend.position = c(0.85, 0.9),
         legend.direction = "horizontal") +
  annotate(geom="text",x=6500,
           y=3500,label= "R² = ~ 79 %") +
  scale_colour_manual(name = "Year", values=c("#03a1fc", "#fc5a03", "#94fc03"))

#print plot
pe_over_ratedcapacity_2019 +  theme(legend.position = c(0.25,0.9))

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

#linear models with rated capacity over commissioning date
lm_rated_capacity_over_time_2019 <- lm(
  amprion_2019$leistung ~ amprion_2019$inbetriebnahme)
summary(lm_rated_capacity_over_time_2019)
plot(lm_rated_capacity_over_time_2019)

#Plot rated capacity over commissioning date with linear trend 2017 - 2019
prated_capacity_over_commission <- ggplot() +
  geom_point(data = amprion_2019,
             aes(x=inbetriebnahme, y=leistung),
             size = 0.4, colour = "#94fc03") +
  geom_smooth(data = amprion_2019,
              aes(x=inbetriebnahme, y=leistung, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
```

```r
  theme_light() +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
  ylim(-1000, 6000) +
  xlab("Commissioning Date") +
  ylab("Rated capacity [kW]") +
  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") +
  geom_hline(yintercept = 3500, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("1997-01-01"),
           y=3300,label="mean of ~ 3,500 kW in 2021", size = 2.5) +
  geom_hline(yintercept = 4500, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("1997-01-01"),
           y=4700,label="Predicted mean of ~ 4,500 kW in 2030", size = 2.5) +
  annotate(geom="text",x=as.Date("2025-01-01"),
           y=0,label= "R² = ~ 70 %") +
  scale_colour_manual(name = "Year", values="#94fc03")

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

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

#linear models with full load hours  over the commissioning date 2015 - 2019
#2015
lm_flh_2015 <- lm(
```

```
  amprion_2015$flh ~ amprion_2015$inbetriebnahme)
summary(lm_flh_2015)
plot(lm_flh_2015)

#2016
lm_flh_2016 <- lm(
  amprion_2016$flh ~ amprion_2016$inbetriebnahme)
summary(lm_flh_2016)
plot(lm_flh_2016)

#2017
lm_flh_2017 <- lm(
  amprion_2017$flh ~ amprion_2017$inbetriebnahme)
summary(lm_flh_2017)
plot(lm_flh_2017)

#2018
lm_flh_2018 <- lm(
  amprion_2018$flh ~ amprion_2018$inbetriebnahme)
summary(lm_flh_2018)
plot(lm_flh_2018)

#2019
lm_flh_2019 <- lm(
  amprion_2019$flh ~ amprion_2019$inbetriebnahme)
summary(lm_flh_2019)
plot(lm_flh_2019)

#plot full load hours over commissioning date with trend
pflh <- ggplot() +
  geom_point(data = amprion_2015, aes(x=inbetriebnahme, y=flh),
             size = 0.4, colour = "#fd00e2") +
  geom_point(data = amprion_2016, aes(x=inbetriebnahme, y=flh),
```

```
            size = 0.4, colour = "#fde600") +
  geom_point(data = amprion_2017, aes(x=inbetriebnahme, y=flh),
            size = 0.4, colour = "#03a1fc") +
  geom_point(data = amprion_2018, aes(x=inbetriebnahme, y=flh),
            size = 0.4, colour = "#fc5a03") +
  geom_point(data = amprion_2019, aes(x=inbetriebnahme, y=flh),
            size = 0.4, colour = "#94fc03") +
  geom_smooth(data = amprion_2015,
             aes(x=inbetriebnahme, y=flh, colour = "2015"),
             method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2016,
             aes(x=inbetriebnahme, y=flh, colour = "2016"),
             method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2017,
             aes(x=inbetriebnahme, y=flh, colour = "2017"),
             method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2018,
             aes(x=inbetriebnahme, y=flh, colour = "2018"),
             method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  geom_smooth(data = amprion_2019,
             aes(x=inbetriebnahme, y=flh, colour = "2019"),
             method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  theme_light() +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
  ylim(0, 4000) +
  xlab("Commissioning Date") +
  ylab("Full load hours [h/a]") +
  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") +
  geom_hline(yintercept = 2300, linetype = 'dashed', size = 0.25) +
```

```
  annotate(geom="text",x=as.Date("1997-01-01"),
           y=2200,label="mean of ~ 2,300 h/a in 2021 with linear trends",
           size = 2.5) +
  geom_hline(yintercept = 2800, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("2000-01-01"),
           y=2900,label="mean of ~ 2,800 h/a in 2030 with linear trends",
           size = 2.5) +
  geom_hline(yintercept = 15000, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("2003-01-01"),
           y=14200, label="> 15,000 MWh/a in 2030 with polynomial models",
           size = 2.5) +
  annotate(geom="text",x=as.Date("2026-01-01"),
           y=800,label= "All R²  ~ 46 - 51 %", size = 2.5) +
  annotate(geom="text",x=as.Date("2026-01-01"),
           y=400,label="p-values all << 0.001", size = 2.5) +
  scale_colour_manual(name = "Year",
                      values=c("#fd00e2", "#fde600",
                               "#03a1fc", "#fc5a03", "#94fc03"))

#print plot
pflh +  theme(legend.position = c(0.35,0.93))

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

A.2 Code chunk 2

```
################################
#geospatial distance estimation#
################################

Sys.setenv(LANG = "en")
pacman::p_load(data.table, tidyverse, magrittr, leaflet, sp, raster, htmltools,
               htmlwidgets, sf, spatstat, rgeos, rgdal, DiagrammeR)

#import data
MaStR_amprion <- read.csv("MaStR_amprion2019.csv")
attach(MaStR_amprion)

#change lat and long to numeric
MaStR_amprion$l_wgs84 <- gsub(",",".", l_wgs84)
MaStR_amprion$b_wgs84 <- gsub(",",".", b_wgs84)
MaStR_amprion$b_wgs84 <- as.numeric(MaStR_amprion$b_wgs84)
MaStR_amprion$l_wgs84 <- as.numeric(MaStR_amprion$l_wgs84)

#load boundaries of RLP
border_sf  <- st_read("Borders_RLP_shape/Landesgrenze_RLP.shp")
border_sp <- readOGR("Borders_RLP_shape/Landesgrenze_RLP.shp")

#create coordinate columns and check CRS
class(MaStR_amprion)
coordinates(MaStR_amprion) <- ~ l_wgs84 + b_wgs84
crs(MaStR_amprion)

#create crs
WGS84 <- CRS("+proj=longlat +datum=WGS84 +no_defs")
crs(MaStR_amprion) <- WGS84
crs(MaStR_amprion)
```

```
#clip those inside RLP
wts_rlp <- MaStR_amprion[border_sp,]
wts_rlp_df <- as.data.frame(wts_rlp)



#convert point layer to in sf format
wts_rlp_sf <- st_as_sf(wts_rlp)
crs(wts_sf)
class(wts_sf)

#transform point layer of wts to flat
wts_rlp_flat <- st_transform(wts_rlp_sf, crs = 6345)
plot(wts_rlp_flat)

#transform border polygon of RLP to flat
border_flat <- st_transform(border_sf, crs = 6345)

##############################
#PPA - Point Pattern Analysis#
##############################

#create ppp formate of WT's
wts_rlp_ppp  <- as.ppp(wts_rlp_flat)
plot(wts_rlp_ppp)

#create owin format
border_owin <- as.owin(border_flat)

#create window of points with borders of rlp and plot
Window(wts_rlp_ppp) <- border_owin
plot(wts_rlp_ppp, cols=rgb(0,0,0,.2), pch=20)

#calculate average nearest neighbor
```

```
mean(nndist(wts_rlp_ppp, k=1))
#~549m -----> seems reasonable

#calculate nearest neighbor
nearest <- nndist(wts_rlp_ppp, k=1)

wts_rlp_distances <- data.frame(wts_rlp_df, nearest)
wts_rlp_distances$nearest <- round(wts_rlp_distances$nearest)



#plot with leaflet
leaflet(data = wts_rlp_distances) %>%
  addTiles() %>%
  addPolygons(data = border_sp,
              color = "#5DADE2",
              weight = 2,
              opacity = 0.6,
              fillColor = "#5DADE200",
              highlight = highlightOptions(weight = 7,
                                           color = "#5DADE2",
                                           fillColor = "#5DADE2",
                                           fillOpacity = 0.3,
                                           bringToFront = TRUE),
              label = "Rheinland-Pfalz",
              group = "Rheinland-Pfalz") %>%
  addMarkers(lng = wts_rlp$l_wgs84,
             lat = wts_rlp$b_wgs84,
             clusterOptions = markerClusterOptions(disableClusteringAtZoom = 10),
             popup = ~paste("<h3> Daten der Windkraftanlage</h3>",
                            "<b>Distance to next WT:</b>", nearest, "<br>"))

#create colum with mwh and area
wts_rlp_distances <- wts_rlp_distances %>%
```

```
  mutate(menge_mwh = round(menge_kwh/1000)) %>%
  mutate(area_m2 = round(nearest^2)) %>%
  mutate(area_km2 = round(area_m2/1000000, digits = 3)) %>%
  mutate(kwh_m2 = round(menge_kwh/area_m2, digits = 3)) %>%
  mutate(d = round(nearest/rotor_m))

#write csv file
write.csv(wts_rlp_distances, "wts_rlp_distances.csv")
```

A.3 Code chunk 3

```
########################################################################
#Analysis of rotor diameter, hub heights and electricity yield per area#
########################################################################

Sys.setenv(LANG = "en")
pacman::p_load(data.table, tidyverse, magrittr, leaflet, htmltools,
               htmlwidgets, gridExtra)

#import data
wts_rlp_distances <- read.csv(
  "result_of_distance_estimation/wts_rlp_distances.csv")

#change date format
wts_rlp_distances$inbetriebnahme <- as.Date(
  wts_rlp_distances$inbetriebnahme, "%Y-%m-%d")

############################
#Analysis of rotor diameter#
############################
wts_rlp_rotor <- filter(wts_rlp_distances, rotor_m != "NA")
wts_rlp_rotor <- filter(wts_rlp_rotor, rotor_m < 200)
sum(is.na(wts_rlp_rotor$rotor_m))
```

```
mean(wts_rlp_rotor$rotor_m)
#86.54686 m

#linear model of rotor diameter over commissioning
lm_rotor <- lm(wts_rlp_rotor$rotor_m ~ wts_rlp_rotor$inbetriebnahme)
summary(lm_rotor)
plot(lm_rotor)

#plot rotor diameter over commissioning date
p_rotor <- ggplot() +
  geom_point(data = wts_rlp_rotor, aes(x=inbetriebnahme, y=rotor_m),
             size = 0.4, colour = "#fde600") +
  geom_smooth(data = wts_rlp_rotor,
              aes(x=inbetriebnahme, y=rotor_m, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  theme_light() +
  ylim(25,170) +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
  xlab("Commissioning date") +
  ylab("Rotor diameter [m]") +
  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") +
  annotate(geom="text",x=as.Date("2025-01-01"),
           y=50,label= "R² = 68.7 % \n p-value << 0.001") +
  scale_colour_manual(name = "Data from MaStR",
                      values="#fde600") +
  theme(legend.position = c(0.3,0.9))


########################
```

```r
#Analysis of hub height#
########################
wts_rlp_nabe <- filter(wts_rlp_distances, nabe_m != "NA")
wts_rlp_nabe <- filter(wts_rlp_nabe, nabe_m < 200)
sum(is.na(wts_rlp_nabe$nabe_m))
mean(wts_rlp_nabe$nabe_m)
#110.3489 m

#linear model
lm_nabe <- lm(wts_rlp_nabe$nabe_m ~ wts_rlp_nabe$inbetriebnahme)
summary(lm_nabe)
plot(lm_nabe)

#plot hub height over commissioning date
p_nabe <- ggplot() +
  geom_point(data = wts_rlp_nabe, aes(x=inbetriebnahme, y=nabe_m),
             size = 0.4, colour = "#fc5a03") +
  geom_smooth(data = wts_rlp_nabe,
              aes(x=inbetriebnahme, y=nabe_m, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  theme_light() +
  ylim(25,220) +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
  xlab("Commissioning date") +
  ylab("Hub height [m]") +
  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") +
  annotate(geom="text",x=as.Date("2025-01-01"),
           y=50,label= "R² = 77.9 % \n p-value << 0.001") +
  scale_colour_manual(name = "Data from MaStR",
```

```
                      values="#fc5a03") +
  theme(legend.position = c(0.3,0.9))

p_nabe

#plot both in one
grid.arrange(p_rotor, p_nabe, ncol=1)

#save plot
ggsave("results_of_analysis/rotor_diameter_hub_height.png",
       plot = grid.arrange(p_rotor, p_nabe, ncol=1),
       dpi = 900,
       width = 7,
       height = 4)

par(mfrow=c(1,1))
#######################################
#Analysis of electricity yield per area#
#######################################

#remove WT's that have distance greater than 1000 m equal to zero
wts_rlp_filtered <- filter(wts_rlp_distances, nearest < 1000 & nearest != 0)

#omit NA values
sum(is.na(wts_rlp_filtered$menge_mwh))
wts_rlp_filtered <- na.omit(wts_rlp_filtered)

#filter those with electricity yield smaller than 10 Mwh and small distance
wts_rlp_filtered <- filter(wts_rlp_filtered, menge_mwh > 20)
wts_rlp_filtered <- filter(wts_rlp_filtered, nearest > 30)

#filter out with electricity yield per m2 above 100 kwh/m2
wts_rlp_filtered <- filter(wts_rlp_filtered, kwh_m2 < 500)
```

```r
#create linear model
lm_e_yield_per_area <- lm(
  wts_rlp_filtered$kwh_m2 ~ wts_rlp_filtered$inbetriebnahme)
summary(lm_e_yield_per_area)
plot(lm_e_yield_per_area)

#calculate average distance in relation to rotor diameter
mean(wts_rlp_filtered$d)
#4.983264

#calculate mean distance again and area consumption with average
mean(wts_rlp_filtered$nearest)
#~417.3347m that means 169,744 m2 or 0.17 km2 per WT
#area of RLP 19847
#total are consumption with 1702 WT's is  289.34 km2 this is about 289,340,000 m2
#that is 1.457 % of RLP
#with a total electricity yield of 6,782 TWh that means 23,439 kWh/m2
#constant power output of 2.675 W/m2
#calculate wind speed with third root of electricity yield per area divided
#by 0.016 * 1.3 * 0.5 = 0.0104
#2.675/0.0104 = 257.2115
#250.9827^(1/3)
#wind speed with 6.359605 m/s required


#calculate actual total mean electricity yield per m2 in data
mean(wts_rlp_filtered$kwh_m2)
#~26.17383 kwh/m2
#Calculate average power per area with 23.3(1000/8765)
#~2.6583 W/m2
#2.6583/0.0104 = 255.6058
#255.6058^(1/3) = 6.346343 m/s wind speed required
```

```
#calculate area consumption of 22 TWh with ~23.3 kWh/m2
#22*(1e+09kwh/23.3 kwh/m2) = 943422522m2 = 943.4225km2 = 4.753477 %
# = 3.168985 times the current area

#calculate area consumption with mean of WT's built after 2010
wts_rlp_filtered_2010 <- filter(wts_rlp_filtered, inbetriebnahme > "2010-01-01")
mean(wts_rlp_filtered_2010$nearest)
#467.9847 m
mean(wts_rlp_filtered_2010$d)
#4.60781 times d
mean(wts_rlp_filtered_2010$area_m2)
#238527.4 m2
mean(wts_rlp_filtered_2010$area_km2)
#0.2385161 km2
mean(wts_rlp_filtered_2010$kwh_m2)
#30.46168 kWh/m2
#3.477361 W/m2


#plot electricity yield per area over commissioning date
p_e_yield_per_area <- ggplot() +
  geom_point(data = wts_rlp_filtered, aes(x=inbetriebnahme, y=kwh_m2),
             size = 0.4, colour = "#00A2ff") +
  geom_smooth(data = wts_rlp_filtered,
              aes(x=inbetriebnahme, y=kwh_m2, colour = "2019"),
              method=lm, se=TRUE, fullrange = TRUE, size = 0.5)  +
  theme_light() +
  ylim(0,80) +
  scale_x_date(limits = as.Date(c("1990-01-01","2030-12-31"))) +
  xlab("Commissioning date") +
  ylab("Electricity yield per area [kWh/m²a]") +
  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") +
  geom_hline(yintercept = 33.5, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("1995-01-01"),
          y=35.5,label="Predicted mean of  ~ 33.5 kWh/m²a in 2021",
          size = 2.5) +
  geom_hline(yintercept = 40.5, linetype = 'dashed', size = 0.25) +
  annotate(geom="text",x=as.Date("1995-01-01"),
          y=42.5,label="Predicted mean of ~ 40.5 kWh/m²a in 2030",
          size = 2.5) +
  annotate(geom="text",x=as.Date("2025-01-01"),
          y=5,label= "R² = ~ 11 % \n p-value << 0.001") +
  scale_colour_manual(name = "Joined data from MaStR and amprion",
                      values="#00A2ff")

#plot
p_e_yield_per_area +  theme(legend.position = c(0.7,0.9))

#save plot
ggsave("results_of_analysis/e_yield_per_m2_over_commissioning_date.png",
       plot = last_plot(),
       dpi = 900,
       width = 7,
       height = 4)



#the model assumes an average of around 33.5 kWh/m2a in 2021
#3.822019 W/m2
#3.822019/0.0104 = 367.5018 (5d)
#3.822019/0.0436 = 87.66099 (3d)
#367.5018^(1/3) = 7.16286 m/s wind speed required (5d)
#87.66099^(1/3) = 4.442241 m/s wind speed required (3d)
```

```
#wind speed of 7.16286 m/s
##calculate area consumption of 22 TWh
#This requires an area of 656716418 m2 = 656.7164 km2 = 3.308895 %
#= 2.20593 times as much WT's

#if average is 40.5 kwh/m2a in 2030
#4.62065 W/m2
#4.62065/0.0104 = 444.2933 (5d)
#4.62065/0.0436 = 105.9782 (3d)
#444.2933^(1/3) = 7.630563 m/s wind speed required (5d)
#105.9782^(1/3) = 4.732299 m/s wind speed required (3d)
#area consumption with demand of 22 TWh
# 543209877 m2 = 543.2099 km2 = 2.736987 % = 1.824658 times as much

#if average is 63.5 kWh/m2a in 2030
#7.2 W/m2
#7.2/0.0104 = 692.3077 (5d)
#7.2/0.0436 = 165.1376
#692.3077^(1/3) = 8.846396 m/s (5d)
#165.1376^(1/3) = 5.486331 m/s (3d)
#area of 346.456 km2 = 1.74 %
```

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.

Heilbronn, November 17, 2021

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Elias Cuadra Braatz