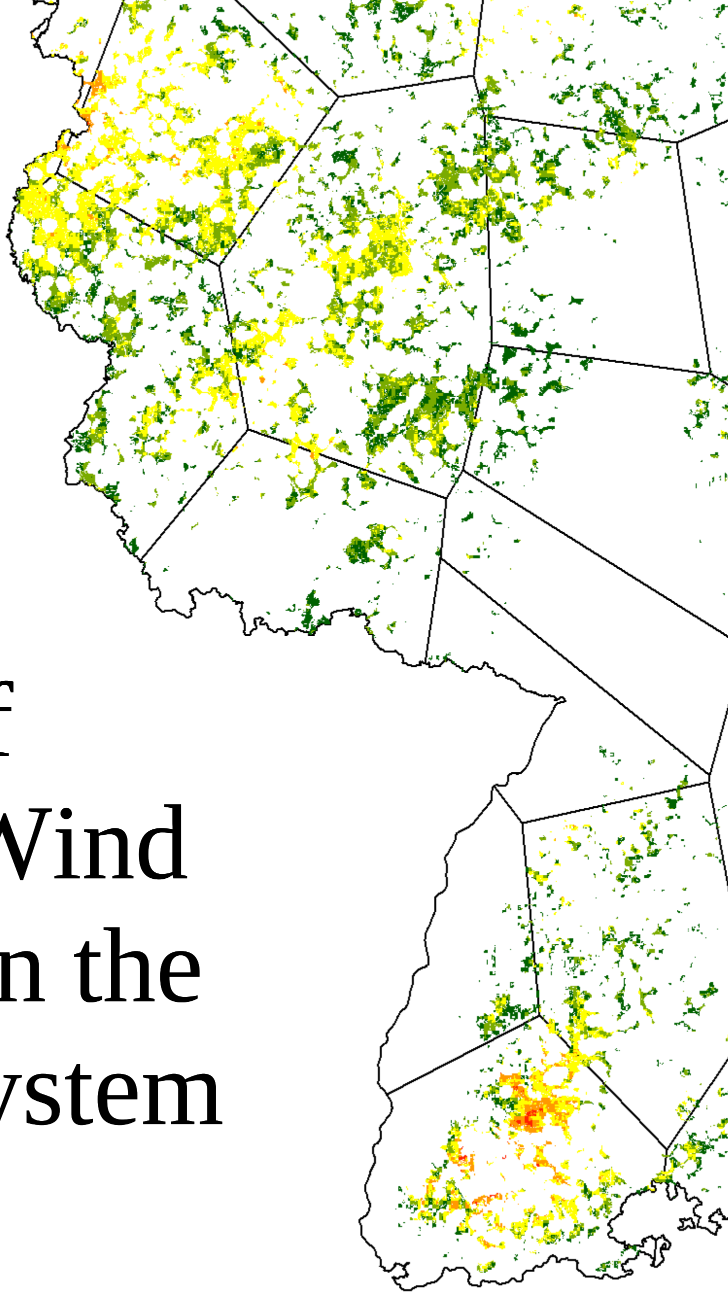

The Effect of Distributed Wind Production on the Necessary System Flexibility

in Germany in the Year 2030

Damian Wimmer
Master’s Thesis, Aalborg University, 4th Semester Master in Sustainable Energy Planning and Management

Synopsis

Title: The Effect of Distributed Wind Production on the Necessary System Flexibility in Germany in the Year 2030.

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Project period: 3rd of February 2014 until the 4th of June 2014

Supervisor: Steffen Nielsen

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Completion: 28th of May 2014

Synopsis:

This report seeks to investigate how the spatial distribution of wind turbines affect the required flexibility in the future German electricity system. The research question is answered in four steps by utilizing a geo information system and an Excel model.

First, the available areas on which wind turbines can be placed, without interfering with other interests, are determined.

Second, two wind turbine distribution scenarios, the best wind site scenario and the even distribution scenario, are determined.

Third, the production profiles of the two scenarios are calculated, considering two different wind turbine types and 70 wind profiles from all over Germany.

Fourth, the residual loads of both scenarios are calculated and the required flexibility of the electrical system is analysed according to the capacity and characteristic.

It is found, that the effect of the higher installed capacity, in the even distribution scenario, surpasses the smoothing effect of the distributed wind turbine placement. Further, the residual load curve of the even distribution scenario is smoother, which results in lower flexibility gradients but the same required flexibility capacity.

Preface

This study is conducted within the fourth semester of the master program in Sustainable Energy Planning and Management at Aalborg University, in the period from the 3rd of February 2014 until the 4th of June 2014. The study is written at the Oeko-Institut e.V. in Freiburg, Germany.

The topic of this report was found as a mutual interest of the host organisation and the author.

The Harvard British method is applied for references, the author's last name and the year of publication are placed in parentheses. The title of non-English resources is left in the original language.

The appendix includes a CD-ROM which contains mainly the developed Excel models. The ArcGIS file geodatabase and project files are provided upon request.

Special thanks are given to Christoph Heinemann and Dr. Dierk Bauknecht from the host organisation Oeko-Institut e.V, who supported the entire project process and made the collaboration possible in the first place.

I also like to thank my university supervisor Steffen Nielsen, for his valuable comments and creative ideas.

Further I would like to say thank you to Lui and obviously Kati for the tremendous motivation and continuous support during the project period.

Damian O. Wimmer

Freiburg, the 28th of May 2014

Oeko-Institut e.V.

Oeko-Institut is a leading European research and consultancy institute working for a sustainable future. Founded in 1977, the institute develops principles and strategies for realising the vision of sustainable development globally, nationally and locally.

Oeko-Institut employs more than 145 staff, including about 100 researchers at three locations in Germany – Freiburg, Darmstadt and Berlin. They complete approximately 300 projects each year, tackling both national and international issues. Work is organised around the subjects of Chemicals Management and Technology Assessment, Energy and Climate, Immission and Radiation Protection, Agriculture and Biodiversity, Sustainability in Consumption, Mobility, Resource Management and Industry, Nuclear Engineering and Facility Safety as well as Law, Policy and Governance. The internship is conducted in the Energy and Climate division in Freiburg.

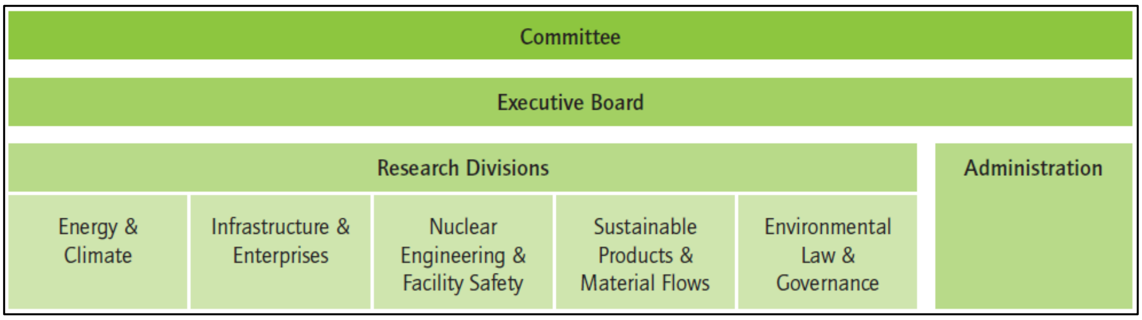

Figure 1: Organizational chart of Oeko-Institut e.V. (Oeko-Institut e.V. 2013).

Based on value-oriented research, the institute provides consultancy for decision-makers in politics, industry and civil society. Key clients are ministries and federal agencies, industrial enterprises and the European Union. In addition, the institute is commissioned by non-governmental organisations and environmental associations. The institute collaborates with research institutions and is active in national and international networks such as in Ecornet (Ecological Research Network).

Oeko-Institut is a non-profit association. Financial resources come mainly from third-party, project-based funding. Contributions and donations made by the association's 2,500 members – including 27 local authorities – guarantee independence. The institute's annual turnover runs to some twelve million Euros.

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List of Abbreviations

GHG	Greenhouse gas
CO_2	Carbon dioxide
EEG	Renewable Energy Sources Act
GGDP	Netzentwicklungsplan (German, meaning “German Grid Development Plan”)
TSO	Transmission System Operator
e.g.	exempli gratia (Latin, meaning “for example”)
ibid.	ibidem (Latin, meaning “in the same place”)
etc.	et cetera (Latin, meaning “and other things”)

Units:

TWh	Terawatt hour
a	Year
km	Kilometre
km^2	Square kilometre
Hz	Hertz
W	Watt
m^2	Square meter
dB(A)	Sound power
GB	Gigabyte

1 Introduction

Due to human activities, like agriculture and the use of fossil fuels, the concentration of greenhouse gases (GHG) increased since the pre-industrial age, defined to 1750. With very high confidence this increases the earth's net radiation[1], commonly known as global warming. Simulation based projections for the mid- to late 21st century with alternative pathways of demographic, economic and technological climate driving forces show, that the climate changes overall unfavourable for humankind. Over most land areas, warmer and fewer cold days, as well as heat waves and heavy precipitation events are expected. Very likely effects are for example water quality problems, soil erosion, reduced agriculture yields and decreased heat, but increased cooling demand. Apparently compensatory effects like increased water demand through heat waves and decreased water scarcity through precipitation events, occur in different regions, which are already troubled by the corresponding weather event. Thus, regional differences are magnified. With a share of 77 per cent of the total anthropogenic GHG emissions in 2004, carbon dioxide (CO_2) is identified as the most important anthropogenic GHG. (IPCC Core Writing Team et al. 2007)

The European Union commits itself to reduce the GHG emissions[2] and thus limit global warming to 2°C compared to the pre-industrial age. Binding goals for the year 2020 exist and are known as the 20-20-20-goals (Comission of the European Communities 2007; Comission of the European Communities 2006; European Parliament & European Council 2009). The second of these goals is to raise the share of renewable energy to 20 per cent of the gross final energy consumption[3]. This goal is broken down to the member states and it is evaluated in section 1.1 that Germany fulfils its goal of increasing the share of renewable energy to 18 per cent of the gross final energy consumption by 2020.

[1] The "Earth's net radiation, sometimes called net flux, is the balance between incoming and outgoing energy at the top of the atmosphere. It is the total energy that is available to influence the climate. Energy comes in to the system when sunlight penetrates the top of the atmosphere. Energy goes out in two ways: reflection by clouds, aerosols, or the Earth's surface; and thermal radiation—heat emitted by the surface and the atmosphere, including clouds. The global average net radiation must be close to zero over the span of a year or else the average temperature will rise or fall." (NASA Earth Observatory 2006)

[2] Also to fulfil the Kyoto Protocol, which sets internationally binding GHG emission reduction targets (United Nations Framework Convention on Climate Change (UNFCCC) 2014)

[3] For the definition please see section 2.1.

Currently no binding goals for the electricity sector with a perspective after the year 2020 exists on a European Union level, but a discourse, initiated in March 2013, is ongoing. The latest document from the European Commission (European Comission 2014) on the discussion is based on the Energy Roadmap 2050 (European Comission 2011b; European Comission 2011a) and includes the results of the Green Paper[4] (European Comission 2013) on the topic. This active and ongoing discourse about the 2030 goals for the European Union shows that the topic is important in the future and that there is the endeavour to set new binding goals. Based on the discussion papers, it can be expected, that the final 2030 goal for the share of renewable energy of the total gross end energy demand is somewhat in the range of 27 per cent. The final goal for the share of renewable energy in the electricity sector is expected to be around 45 per cent.

1.1 Renewable Energy Policy in Germany

Renewable energy policy has a long history in Germany and goes back to the "Stromeinspeisegesetz", the first German feed-in law from 1991. Within this law local utilities have been obliged to buy electricity produced by wind and solar at a price of 90 per cent of the end consumer price (Bechberger 2000). Nine years later, in the year 2000, the first version of the current feed-in law, the Renewable Energy Sources Act (EEG) came to law. Since then the share of renewable energy of the gross final energy consumption[5] of Germany increased from 3.9 to 12.6 per cent in 2012 (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) 2012b). Especially the electricity sector increased the share of renewable energy in the same timeframe from 6.8 to 22.9 per cent. Despite a reduction of the share of renewable energy of the gross final energy consumption from the year 2007 to 2008 the share increased nearly linear every year. Based on this historical development with an average increase of 0.73 per cent per year, it can be expected that Germany fulfils its overall European Union goal for the year 2020 of 18 per cent, with approximately 18.2 per cent (own projection, based on data from: Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) 2012).

[4] "Green Papers are documents published by the European Commission to stimulate discussion on given topics at European level. They invite the relevant parties (bodies or individuals) to participate in a consultation process and debate on the basis of the proposals they put forward. […]" (European Union 2014)

[5] For the definition please see section 2.1.

Within the German Energy Concept (Federal Ministry of Economics and Technology (BMWi) & Federal Ministry for the Environment 2010), published in September 2010, renewable energy goals for the years after 2020 are defined. The goal for the renewable energy share of the gross final energy consumption is set to 30 per cent for the year 2030, which is higher than the still under discussion European Union goal of 27 per cent. Regarding the electricity sector the goal for the renewable energy share of the gross final electricity consumption is set to 50 per cent in the year 2030. Again, compared to the currently discussed 2030 European Union goal of 45 per cent, the German goal is ambitious.

As a reaction to the nuclear accident in Fukushima[6] the German Government changed the just explained Energy Concept on the 6th June 2011 in regards to the use of nuclear energy (Federal Ministry of Economics and Technology (BMWi) & Federal Ministry for the Environment 2010). Before that, nuclear energy was supposed to play a transfer role to an energy system based on renewable energy. But with the "Thirteenth Amendment to the Atomic Energy Act" (BGBl I 2011 p. 1704) eight nuclear power plants have been immediately phased out while the remaining nine nuclear power plants phase out between 2015 and 2022 (Bundesregierung 2011). The other parts of the Energy Concept remain unchanged.

1.1.1 Germany's Electricity Production in 2033

The just described European and German policies set overall political goals for the future. Because of various uncertainties in the future, like the economic and technological development, those goals shall be understood as guidance and the actual percentage values may differ, but be within a similar range. (Federal Ministry of Economics and Technology (BMWi) & Federal Ministry for the Environment 2010)

Germany's overall political goals are translated to a more detailed level by the German Grid Development Plan (GGDP)[7]. The newest GGDP includes the year 2033 and its projected production data is analysed here.

[6] "Following a major earthquake, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a nuclear accident on 11 March 2011. All three cores largely melted in the first three days […]" (World Nuclear Association 2014)

[7] For more detailed information about the GGDP and its creating procedure, see section 2.1

In **Figure 2** Germany's net electricity production[8] and the net electricity production from renewable energy sources is seen in shares of energy sources, divided in the left and right circle respectively. The percentages are calculated with the assumption, that no renewable energy is exported[9]. In total 68 per cent of the electricity is produced by renewable energy sources and thus the political goal of 50 per cent is surpassed. This rather high share of renewable energy might be necessary to fulfil the GHG reduction as primary goal. Besides that, the GHG goal is surpassed by 6 per cent, and the high share of renewable energy is not further explained in the GGDP.

As it can be seen from the right circle in **Figure 2** the main share of renewable electricity in 2033 is produced by wind power. More precisely, onshore wind power produces a quarter of the total net electricity production, followed by offshore wind power with 19 per cent.

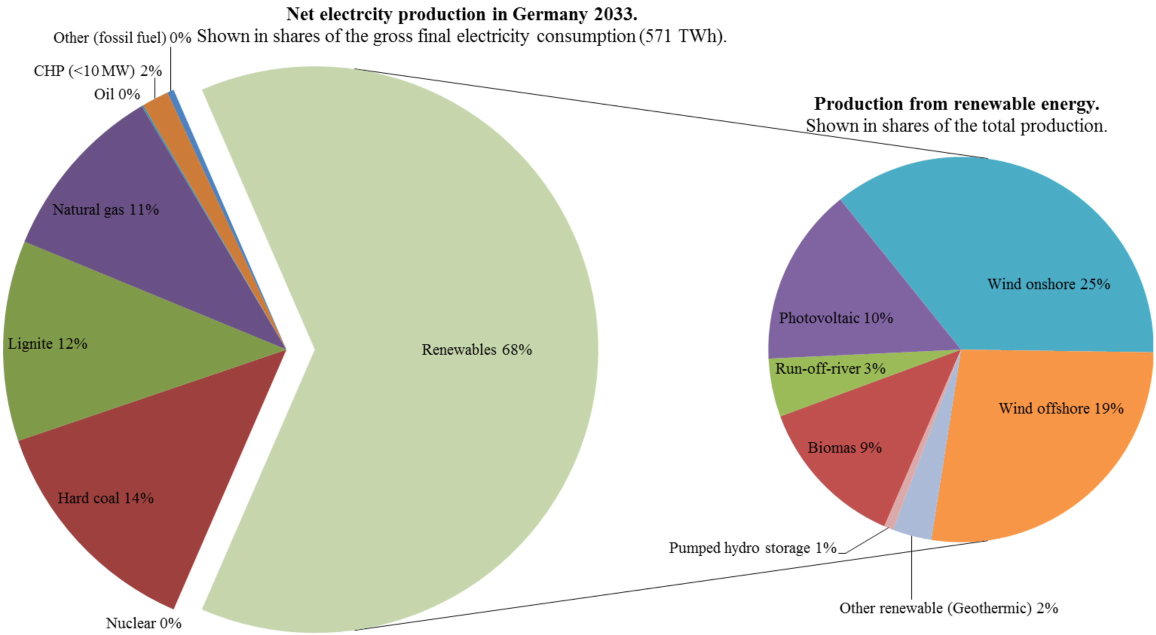


Figure 2: Net electricity production of Germany in 2033. (Own figure, based on data from: 50Hertz Transmission GmbH, Amprion GmbH, et al. 2013)

[8] For the definition please see section 2.1.
[9] This assumption is discussed in the methodology section 2.1.

1.1.2 Onshore Wind Power Potential in Germany

Based on absolute numbers, from the GGDP, onshore wind power has a net electricity production of 140.7 TWh per year with an installed capacity of 66.3 GW. This equals to an average of 2,122 full load running hours per year. In the following it is pondered, if there is even enough spatial and wind potential in Germany to reach these dimensions. It seems sensible to determine the potential with the following steps:

First, the spatial potential has to be determined from a planning perspective. Usually this is done by ruling out unsuitable areas or areas with alternative, non-energy related land use, such as settlement-, infrastructure- and nature protection areas. Second, the annual average wind speed is determined for the usable areas.

In a third step, wind turbines are placed on the available areas and the annual production is calculated according to the respective wind speeds and a wind power production curve. In most studies the turbines are first placed on the spot with the highest wind potential, in other words with the highest wind speeds. The land use of the turbines cannot exceed the spatial potential.

Several studies (BWE Bundesverband WindEnergie 2012; Lütkehus et al. 2013; McKenna et al. 2014) conduct a wind power potential study for onshore wind power in Germany. In general the just described methodology is applied in all of them, but different assumptions are made within the steps. For example, different areas are considered usable, different turbine types are applied and differently detailed data is used. The results of these studies can therefore not be compared. The results, illustrated in **Table 1** show a variation between 855 and 2,898 TWh of wind power potential per year. In any case, the planned GGDP production of 140.7 TWh per year can be ranged as realistic, since it is about a sixth of the lowest potential value. The same is true for the planned installed capacity of 66.3 GW.

Table 1: Key-results of three onshore wind potential studies for Germany.

	Lütkehus et al. 2013	BWE Bundesverband WindEnergie 2012	McKenna et al. 2014
Spatial potential	49,361 km²	42,174 km² [10]	41,623 km²
Installable capacity	1,188 GW	722 GW	367 GW
Resulting production	2,898 TWh/a	1,495 TWh/a	855 TWh/a

1.2 Wind Power Integration through Flexibility Options

In the future German electricity system, in 2033, approximately 44 per cent of the gross final electricity consumption is produced by on- and offshore wind power (50Hertz Transmission GmbH et al. 2013). Since wind produces nearly half of the demand, it is the main producer. Electricity production from wind power is intermittent, because it is dependent on wind speeds. The intermittency of the electricity production in the system is moreover reinforced since photovoltaic, with a 10 per cent share of the gross final electricity consumption, has also an intermittent electricity production. With such a high share of wind power and photovoltaic, the future electricity system is characterised by intermittent producers (Agora Energiewende 2012).

Coming back to the focus technology wind power[11], the current German feed-in law EEG determines, that the produced electricity has to be integrated in the system. Even if the EEG would not exist in the future it is meaningful to use and integrate the electricity produced by wind power to a large extend, because it has short term marginal cost just above zero (Agora Energiewende 2012). This is because the total cost for a wind turbine can be described by an initial investment to build the turbine etc. and variable running cost for example for operation and maintenance. The running cost are low, at about 4 per cent per year of the capital cost (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) 2012a).

Market integration of intermittent production implies to match production and demand for example through different flexibility options. Based on a yet unpublished research

[10] This figure is based on own extrapolation since it is not given in the public version of the study.
[11] Some of the statements can be transferred and are valid for photovoltaic.

project (Heinemann et al. 2014), flexibility options are defined and grouped in four categories. In the following a short outline of each category is given:

- Demand side management: Using flexible consumers, the demand is adjusted to the production. Based on process adjustment and technical optimisation a high potential is seen in the industrial sector (Agora Energiewende 2012). But also smaller businesses and private households have potential in the future (Agora Energiewende 2012).
- Production management: Controllable power plants produce the residual deficit, if the intermittent production is not sufficient. An, although economically unreasonable, option is to shut down intermittent power production in hours of excess electricity.
- Storage: Pump hydro storage, compressed air storage, batteries, also in electric vehicles and other options, can store electricity in surplus hours and provide in deficit hours.
- Linking energy sectors: In hours of renewable excess electricity, the excess electricity can be transferred to other energy systems. Examples are the heat and mobility sector which can use hot water or hydrogen, produced by excess electricity.

The electrical grid is not a flexibility option comparable to the above standing. Nevertheless the grid can help to reduce the necessary system flexibility[12] in the first place and provide access to flexibility options. Further it connects production and demand, also over great distances and therefore contributes to a smoother residual load profile (Agora Energiewende 2012).

Another approach to integrate the intermittent renewable energy production is to smoothen[13] the overall production by optimising the spatial distribution of the intermittent power plants.

[12] Please see section 2.1.
[13] The term "smoothen" describes reduced maxima and smaller hourly gradients.

1.3 Smoothing the Power Output of Wind Turbines

The necessary system flexibility can be covered by flexibility options, as explained in the previous section. This approach remediates the symptom, but does not eliminate the cause of the problem. However, smoothing[13] the production intervenes already in the production stage.

The fluctuation in the wind turbine production can be divided into short and long term fluctuation. Short term fluctuation describes time periods up to minutes and long term fluctuations everything above that up to a couple of days. (Czisch & Ernst 2001)

Based on a correlation[14] analysis of the power output change of two wind turbines with a distance of just 170 m, it is found by (Czisch & Ernst 2001) that the output is mostly uncorrelated for short terms up to one minute. Short term fluctuation is smoothened significantly already with two closely located turbines and the smoothening effect increases with the number of turbines (Czisch & Ernst 2001; Giebel 2000; Katzenstein et al. 2010). Since it is common practise and in general favourable to build wind farms instead of single turbines, short term fluctuation is reduced to negligible values and is therefore not further discussed in this report.

For long term fluctuations it is found in general, that the wind speed correlation decreases with an increased distance between the turbines (Giebel 2000; Czisch & Ernst 2001; Grothe & Schnieders 2011).

Giebel conducted a correlation analysis, with one value every three hours from 60 meteorological stations in Europe. He found that the average wind speeds become uncorrelated with a distance of about 1,500 km between the measurement stations. That equals to a distance from the very North of Germany to the Middle of Italy. Nevertheless, considering correlation between single measurement stations and not just the average, many stations are already uncorrelated at about 450 km. An exceptional example is the Italian island Sardinia, where two measurement points with just 170 km distance have a very low correlation value. (Giebel 2000)

[14] A low correlation „[…] means that the time series add up to a smoother time series, while time series with high correlation coefficients just add their variability.“ (Giebel 2000)

Giebels findings are consistent with Czisch and Ernst (Czisch & Ernst 2001). They analysed 176 wind power output curves, measured with ten values per second, in regard to different time averages. Time averages of 5 minutes and 30 minutes do not correlate anymore within a few kilometres. The hourly time average becomes uncorrelated below a 100 km distance. The four hour average is consistent to Giebels three hour averaged data and has a low correlation at about 350 km. Considering longer time averages of 6 hours, 24 hours, 48 hours and seven days, the values become uncorrelated at around 1,500 km. This distance is considered to be the extent of a typical weather pattern in Europe (Giebel 2000). For a monthly average, measurements become uncorrelated at around 2,500 km, which equals to the distance from the very North of Germany to the North of Africa.

For Germany, with a width of about 650 km and a length of about 870 km, smoothing effects through the spatial distribution of wind turbines are expected based on the results of the just presented studies. Nevertheless, these smoothing effects might only last within a short timeframe up to 5 hours.

Two recent studies (Agora Energiewende 2013a; Mono et al. 2014) for Germany support the thesis that smoothing effects through spatial distribution are possible in general. Further, especially Mono finds that the combination of wind and PV, at the same site, has significant smoothing effects as well. However both studies do not evaluated how the smoothing effect of the renewable energy production affects the necessary flexibility capacity in the electricity system.

1.4 Research Question

The German Grid Development Plan suggests onshore wind power as the main electricity producer in the year 2033. Based on historical development, current policies, an active discourse about renewable energy in Germany, and sufficient land area and wind potential it is expected that this high share of wind power is reached.

With a high share of onshore wind power, reinforced by photovoltaic, the intermittent electricity production increases, but integration is obligatory. Integration can be achieved through flexibility options, like storages, or by smoothing the production curve. This leads to the research question of this report:

How does the spatial distribution of wind turbines affect the necessary flexibility in the future German electricity system?

The research is guided by the following sub- research questions:

- Where can turbines be located?
- Based on current studies: With which distribution scenarios can wind turbines be spatial distributed to the available area?
- How does the production profile change with different spatial distribution?
- Taking the demand into account: How does that influence the necessary flexibility in the system?

1.5 Delimitations

The following delimitations apply for this report:

- The timeframe is set around the year 2030, since this is the topic of current discussions on a European level and in Germany. It is within a foreseeable timeframe and for Germany detailed data is available.
- Social acceptance is not considered for the wind turbine placement.
- Only onshore wind power is considered, because it is the main, intermittent electricity producer in the future. Further it is a highly fluctuating resource, as explained in section 1.2, which makes it an important research topic. The effect of neglecting other renewable energy production is discussed in section 4 on page 73.

- Offshore wind power is not considered because it is first of all not the main producer and because it is questionable if it will develop as expected, due to general economic and technological risks.
- Technical options to smoothen the wind turbine power output like pitch angel control systems are not considered[15].
- Transmission losses and transmission capacity shortage is considered to be non-existent. This assumption is sometimes called the copper plate assumption.
- The German electricity sector is seen without connection to other energy sectors, e.g. the heating sector and without connection to other countries to stay within the given timeframe.

1.6 Structure of the Study

As it is seen in **Figure 3**, the report is structured according to the four sub-research questions. In the following, the connection between the research question and the single chapters is explained.

In chapter 2, the **Methodology** of this report is developed and explained. In the first four sub chapters definitions are given, the used data is presented and the reference turbines are determined. In the following four sub chapters, 0 to 2.8, the methods to answer the four sub research questions are presented. The sequence of the sub chapters is the same as the sequence of the sub research questions.

In chapter 3, the **Results** are presented. This chapter also follows the sequence of the sub research questions. First the available wind turbine area is shown. Then the wind turbines are distributed to the available area and subsequently the production profiles are calculated. During the analysis of the production profiles it is found, that the respective sub research question cannot be answered finally, which is why two additional scenarios are calculated and analyses. In the last sub chapter the research question is answered.

In chapter 4, the **Discussion**, the results are discussed. This is done in regard to the frame of the report, its limitations, and also from a broader angle.

[15] For more information about power smoothing by controlling the kinetic energy of the inertia, pitch angel control systems and controlling the DC-link voltage see Howlader et al. 2013.

Chapter 5, the **Conclusion**, concludes the report.

In chapter 6, **Alternative Methodological Approaches** are presented and it is discusses why other approaches have been used in this report.

The **Bibliography** and the **Appendix** are found in chapter 7 and 8. A CD-ROM is part of the appendix.

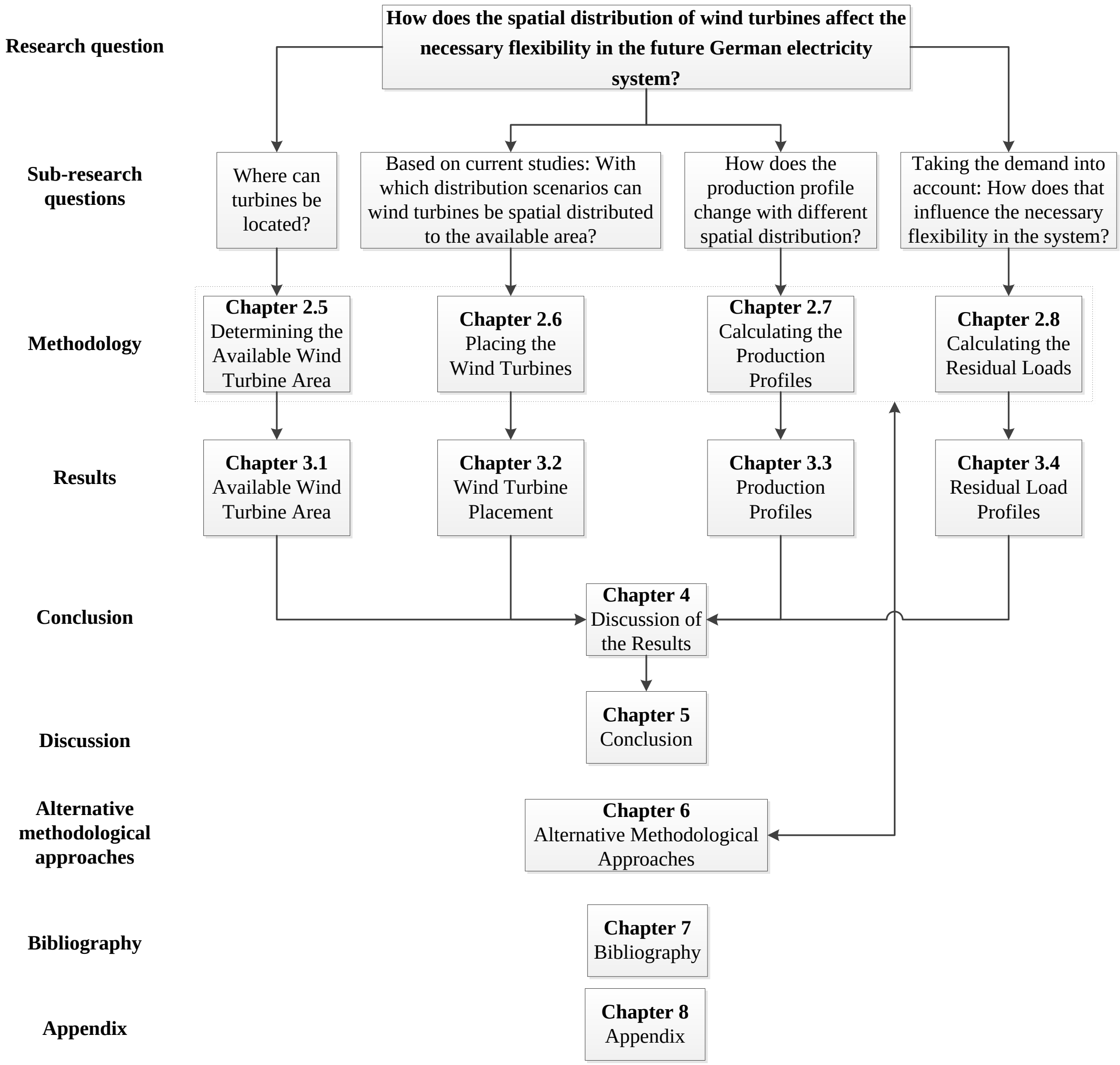


Figure 3: Structure of the report.

2 Methodology

The research question of this report is answered by analysing different spatial distribution scenarios of wind turbines. **Figure 4** shows the main steps conducted in this report.

First of all, available wind turbine placement areas are determined from a planning perspective. This is done by ruling out areas with other, non-energy related land use, such as settlement-, infrastructure- and nature protection areas or for other reasons unsuitable areas. If necessary those areas are equipped with a buffer zone around them to account for visual influence and noise emissions from the wind turbines.

In a second step the spatial wind turbine distribution scenarios are determined through literature research and an internal workshop. According to the scenarios the wind turbines are placed on the available area. The number of turbines placed is limited to the sum of their annual production, so that all scenarios meet the reference production and be comparable among each other.

Subsequently the hourly production of each scenario is calculated and aggregated for Germany. After subtracting the annual hourly production from the annual hourly demand, the resulting residual load curves are analysed according to their necessary flexibility.

The first work steps are conducted with a geographic information system (GIS), the calculation of the production and the analysis of the residual load is done with Microsoft Excel 2010™.

Figure 4 illustrates where the detailed methodology description and the results can be found in this report.

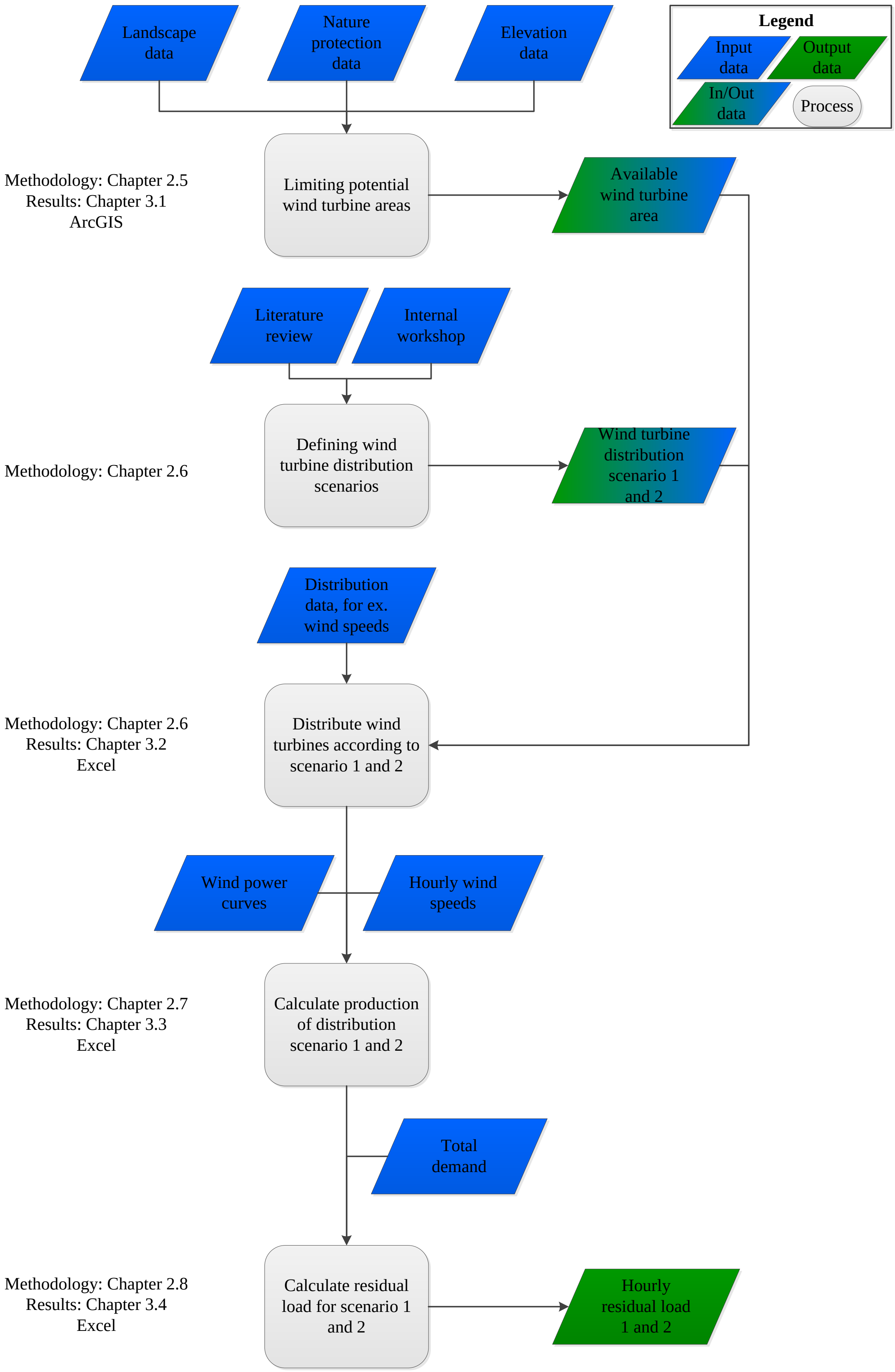


Figure 4: Methodology overview and structure.

2.1 Technical Terms and Definitions

A number of technical terms are used consistently in this report. Since more than one definition of these terms can be found in the literature, the technical terms used within this report, printed in bold, are defined in the following.

The **Gross Final Energy Consumption** is defined, based on the European Renewable Directive 2009/28/EC Par. 2(f), as:

- "[…] the energy commodities delivered for energy purposes to industry, transport, households, services including public services, agriculture, forestry and fisheries,
- including the consumption of electricity and heat by the energy branch for electricity and heat production and

including losses of electricity and heat in distribution and transmission; […]". (European Parliament & European Council 2009)

The **Net Electricity Production** is defined to be the total electricity production excluding

- the own consumption of electricity producing and
- conversion and transmission losses,

but including the exported electricity.

The **Share of Renewable Energy of the Gross Final Electricity Consumption** is calculated by using the following formula:

$$share_{re}\ [\%] = \frac{\sum net\ electricity\ production\ from\ renewable\ energy\ \left[\frac{TWh}{a}\right]}{\sum gross\ final\ electricity\ consumption\ \left[\frac{TWh}{a}\right]} * 100$$

with renewable energy defined and grouped by the GGDP to be (50Hertz Transmission GmbH et al. 2014):

- Biomass
- Run-off-river
- Photovoltaic
- Wind onshore
- Wind offshore
- Other renewable
- Pumped hydro storage (electricity consumed is included in the gross final consumption)

and the gross final electricity consumption as just defined.

In the numerator, the produced but possibly exported electricity is included. In the denominator the import / export balance is considered. In the year 2033 Germany is a net electricity exporter.

It can be argued, that it is the electricity produced by renewable energy which is exported and therefore the export should be subtracted from the renewable energy production in the numerator. That would reduce the share of renewable energy from 68 per cent to 60 per cent (see section 1.1.1 for comparison). On the other hand it can be argued that the inflexible must run power plants[16], like production based on lignite, is responsible for the export.

This discussion is beyond the scope of this report and therefore the share of renewable energy is defined as the production from renewable energy, including the potential export, divided by the gross final electricity consumption.

Necessary System Flexibility: **Figure 5** shows a schematic of a typical, sorted residual load curve of an electricity system in which the whole demand, but only the fluctuating production is considered. As it can be seen production and demand match just for a few hours. In more hours, production and demand do not match, which results either in a residual load (deficit) or in excess electricity (surplus). To integrate this excess electricity, in other words to transfer the area on the negative side of the x-axis to the positive side, the system needs to be flexible. Then, additional flexibility might be

[16] Units with a certain minimum production. Originally constructed to provide base load production.

necessary to produce the residual deficit. In this report the term “necessary system flexibility” is used to sum up the flexibility needed to balance the electricity system. The necessary system flexibility is later described in regard to absolute amounts (A), maxima (B) and ramp rates in different hours. The ramp rates are analysed in an unsorted graph and therefore not shown in **Figure 5**.

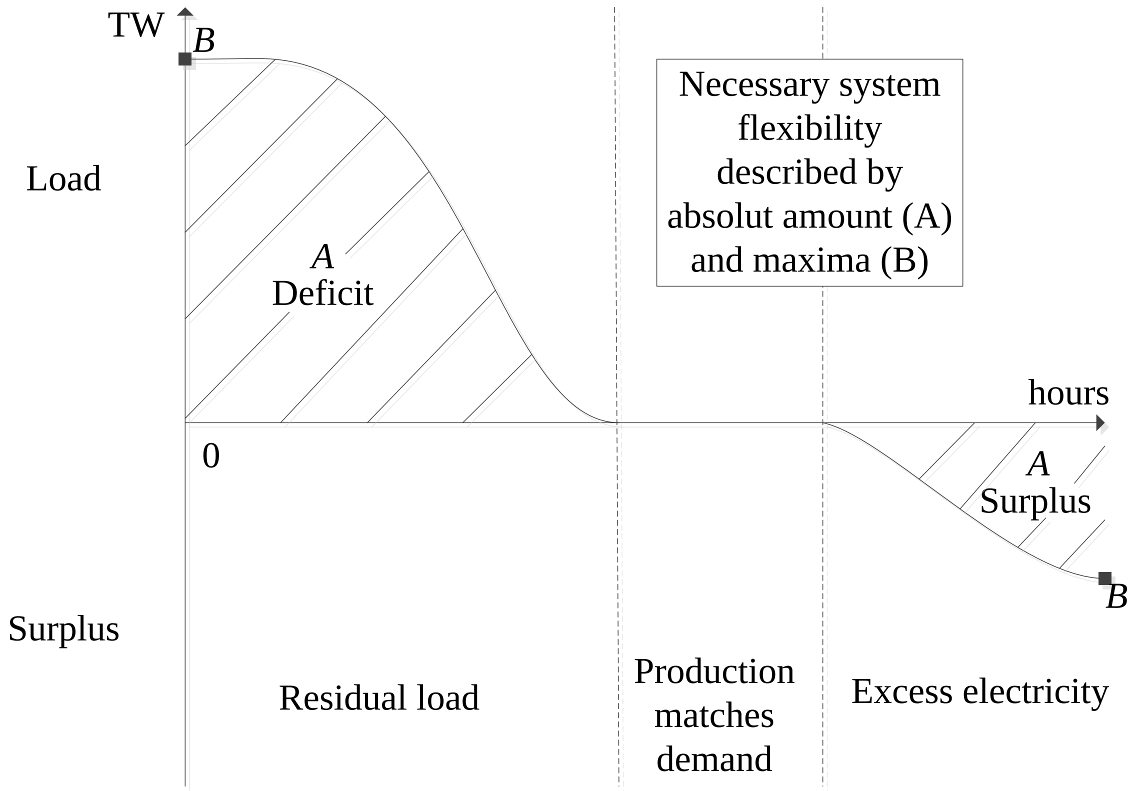


Figure 5: Necessary system flexibility illustrated by a schematic sorted residual load curve for one year.

The German Grid Development Plan (GGDP): “The Grid Development Plan […] describes the measures that are required over the next ten [A/N: and twenty] years for the necessary expansion and restructuring of the German extra-high voltage land grid in order to guarantee safe and reliable network operation […]” (50Hertz Transmission GmbH et al. 2014). These measures are determined, also by projecting the future electricity production and demand, mainly based on a technological, political and societal framework. The GGDP is created annually from the four German Transmission System Operators (TSOs) under consultation of the public, approved by the Federal Network Agency (FNA) and at least all three years converted into a law. The newest, approved version is from 2013 with 10 and 20 years projections for 2023 and 2033. Because of the described complex and broad multi- stage validation process, the GGDP's production and consumption data for 2033 is used in this report. (50Hertz Transmission GmbH et al. 2013)

2.2 Geographic Information System

"GIS is a computer system designed to capture, store, manipulate, analyse, manage, and present all types of geographical data." (ESRI 2011)

In this report a GIS is deployed, for example to determine suitable wind turbine areas and link them to wind speeds. Several different GIS software is available for free or to purchase. Here the commercial software ArcGIS 10.2.1[17] is used, since it provides the necessary functions and tools for this report. The license is provided by the university.

Considering the large study area of this report, the here processed spatial data is mainly of high detailed level. The highest vector data resolution is 1:250,000 and the highest raster data resolution is 100 m x100 m. This guarantees accuracy, but comes along with large file sizes and high requirements for working memory and computing power. Unfortunately the accessible computing resources could not process all data with full details. Therefore some data had to be simplified to achieve acceptable computing performance or even to enable processing. The underlying thought is thereby always to keep as much details as possible. Finding this trade-off is iterative, hence time demanding and more than once try and error based.

[17] For more information about ArcGIS please see: www.esri.com/software/arcgis

2.3 Spatial Data Basis

The following **Table 2** gives a short description of the used spatial data.

Table 2: Overview of the spatial data basis.

Data name	Content	Type and scale or resolution	Source	Updated
DLM250	Digital Landscape Model with settlement areas, infrastructure, landscape and nature protection areas	Vector, 1:250000	Federal Agency for Cartography and Geodesy (BKG)	Depending on the data theme between 2006 and 31.12.2013
DGM200	Digital Elevation Model	Raster, 100 x 100 m	Federal Agency for Cartography and Geodesy (BKG)	Depending on the data theme between 2002 and 2012
BfN nature protection	Flora-Fauna-Habitats (FFH) and Special Protection Areas (SPA) for birds	1: 25000	German Federal Agency for Nature Conservation (BfN)	31.12.2013
DWD annual average wind speeds	Annual average wind speeds from 1981-2000 in 80 m height	Raster, 1 x 1 km	German Weather Service (DWD)	Historical data
DWD hourly wind speeds	Hourly wind speeds for the	70 point datasets	German Weather	Measured historical data

	year 2011		Service (DWD)	
CORINE land cover	Land cover data in 44 categories	Raster, 100 x 100 m	European Environment Agency (EEA)	Updated 2009 but based on 1990 data

The DLM250 data (Bundesamt für Kartographie und Geodäsie 2014b) contains different landscape themes for Germany. The scale of 1:250000 is the smallest available for whole Germany, but small settlements and farmsteads are not marked. Smaller scales are only available on a federal state level and would therefore result in more computing, which is why it is not used in this report. The data is mainly used to determine the available wind turbine area, but also as background data for maps in this report.

The DGM200 data (Bundesamt für Kartographie und Geodäsie 2014a) is provided as raster data and each raster field contains the average height of the respective area. The data is used to exclude very steep areas as wind turbine sites.

The BfN nature protection data (Bundesamt für Naturschutz 2014) is provided as vector data and contains Flora-Fauna-Habitat-and bird protection areas for Germany. This data is also used to limit the wind turbine area.

The DWD historical annual average wind data (Deutscher Wetterdienst 2014a) is collected from 1981 to the year 2000 and provided as raster data in 80 m height. The data is based on measurements from about 200 weather stations distributed over Germany. This long term average is converted to the turbine height and used as fundamental data for the distribution scenarios.

The CORINE land cover (European Environment Agency (EEA) 2009) is provided as raster data and contains the land cover according to 44 categories. It is used to extrapolate wind speeds from one height to another, which is dependent on the land cover.

The DWD hourly wind speed data (Deutscher Wetterdienst 2014b) is provided as historical measurements for the 70 public available weather stations in Germany. The data is used for the calculation of the hourly production profiles and therefore essential for the result of this report. Only few hours have been missing in the dataset. Single missing hours are replaced by the average of the hour before and after. The longest period of eight hours is replaced by the same hours of the day before. The annual average wind speed of the hourly data differs in two cases[18] drastically from the long term hourly wind speeds. In these two cases the hourly wind profile has been scaled up to fit better to the long term average wind speed. It is considered, that by doing so also the wind speed frequency of the profile changes. This manipulation may have an error margin. Therefore, for smaller differences between the long term average and the hourly average the data is not adjusted, to preserve the original measured profile. A method to match the long term average wind speed with the profile is deployed and discussed in section 1 on page 81.

2.4 Reference Turbines

A recent report (Agora Energiewende 2013a) and the corresponding discussion paper (Agora Energiewende 2013b) investigate the expected technological wind turbine development until 2033. In general it is found, that the current trend to distinguish between high- and low wind speed turbines will develop[19]. The report finds further, that the turbines rated power will increase as well as the rotor diameter and the turbine height. According to the report the average turbines in the year 2012 are roughly in the 2 MW class with a hub height of about 90 to 120 m and a rotor diameter of about 85 to 90 m. For the year 2033 the average turbine is expected to be in the 4 MW class, with a hub height of 120 to 150 m and a rotor diameter between 125 and 140 m.

The average lifetime of an onshore wind turbine is considered to be 20 years (Energinet.dk & Energi Styrelsen 2012). Therefore the oldest turbine in 2033 is based on the technological state of the art from today. The, in this report used, high- and low wind speed reference turbines shall therefore represent a mixture over the next 20 years. Unfortunately the necessary wind power curves[20] of such future turbines could not be obtained or estimated within this report.

Therefore state of the art high- and low wind speed turbines, for which wind speed power curves are public available, are used in this report. A recent wind potential report

[18] The measurement station in Kempten and Oberstdorf, which are both in the very South of Germany in the same valley.
[19] See section 2.4.1 for more information about the difference between high and low wind speed turbines.
[20] For a definition of "wind power curve", please see section 2.4.1.

from the German Federal Environment Agency (Lütkehus et al. 2013) analysed which turbines can be considered to be state of the art. Based on this report the turbines shown in **Table 3** are used as reference turbines. Other manufactures provide turbines in similar categories, but no corresponding wind power curves were provided.

Both turbines offer a noised reduced sound power mode, which is not used in this report. That affects the in section 0 determined available areas, the number of necessary turbines to meet the reference production and the hourly production curve, but always in minor way. It is considered in the discussion in section 4.

Table 3: Technical data of the reference turbines.

	Low wind speed turbine (LWST) Enercon E-115	High wind speed turbine (HWST) Vestas V105
Application according to wind speed in 140 m height	< 7.5 m/s	≥ 7.5 m/s
Rated power	3.0 MW	3.3 MW
Rotor diameter	115m	105 m
Hub height	140 m	100 m
Specific area	3.46 m²/kW	2.62 m²/kW
Sound power level (based on Lütkehus et al. 2013)	105.2 dB(A)	105.6 dB(A)
Minimal distance between two turbines	460 m	420 m
Land area use per turbine	138,544 m²	166,190 m²

The minimal distance between two turbines is defined to be four times the larger rotor diameter (Seifert et al. 2003; Lütkehus et al. 2013).

Figure 6 shows the DWD annual average wind speeds for Germany. Red marked are all areas where the average wind speed in 140 m height is greater than 7.5 m/s and therefore a high wind speed turbine would be placed. In white areas the average wind speed is below 7.5 m/s and therefore the low wind speed turbine would be placed. Black areas contain no data, here these are just lakes and rivers. Already now, without considering areas unsuitable for wind turbines, it is seen that less high wind speed areas are available in Germany. Just the very North, the very South and the Central German Uplands offer enough wind potential for high speed turbines.

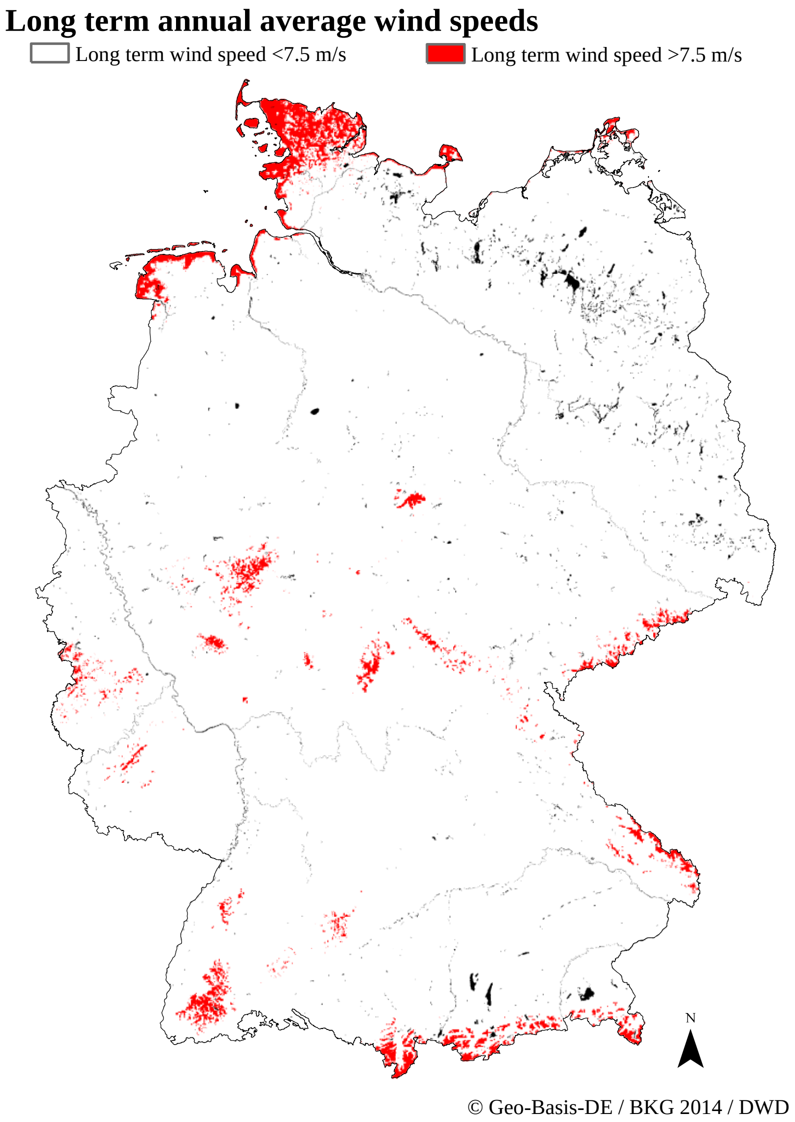


Figure 6: Wind speeds grouped to the high and low wind turbine category.

2.4.1 Wind Speed Power Curve

The wind speed power curve shows the power output of a specific wind turbine as a function of the wind speed. **Figure 7** shows the wind power curves of the low (blue) and high (red) wind speed reference turbines used in this report at a constant air density of 1.225 kg/m³.

Low wind speed turbines are mainly characterised, compared to high wind speed turbines by their high specific area[21], which is the ratio between the rotor swept area and the rated power. As **Table 3** shows, the specific area is mainly influenced by the swept area and not such much by the difference in rated power.

[21] For more information about specific area and specific capacity, please see (Gipe 2013).

Figure 7 shows, that the low wind speed turbine (blue) reaches its rated power output already at a wind speed of 12 m/s compared to 14 m/s of the high wind speed turbine (red). Also the cut- in wind speed, where the turbine starts producing electricity is lower. The here shown low wind speed turbine is in general favourable for wind speeds up to 11 m/s compared to the high wind speed turbine. This is because the compared turbines are rather extreme examples of their respective category. Wind speeds between two integer values are linear interpolated.

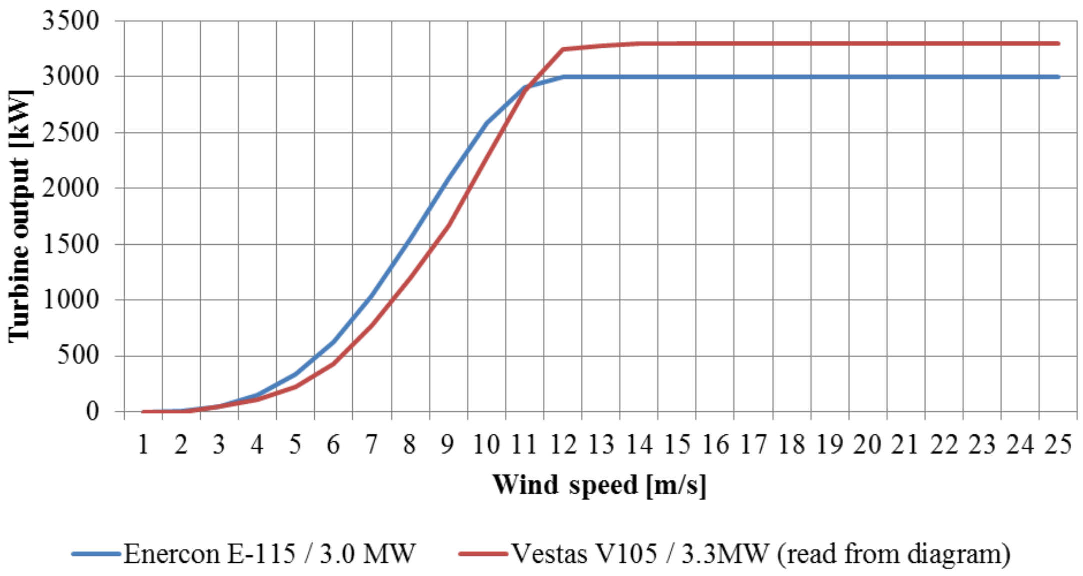


Figure 7: Wind power curve of the low (blue) and high (red) wind speed reference turbines (own figure, based on data from ENERCON GmbH 2013; Vestas Wind Systems A/S 2013).

The low wind speed turbine runs with more full load running hours, since the wind speed necessary for rated power is lower. This results in a more constant production curve (Agora Energiewende 2013a).

The high wind speed turbine is in favour in areas with high wind speeds, because it can produce more output. Further the high wind speed turbine has lower construction cost due to the smaller rotor diameter and the smaller hub height. This reduces the specific production cost in high wind speed areas.

2.5 Determining the Available Wind Turbine Area

Mainly because of other usages or environmental considerations not all areas in Germany are suitable for placing wind turbines. In practice potential wind turbine sites have to fulfil national laws[22], state laws[23], fit in the land development plan and pass an environmental site assessment[24] (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) 2014). Eventually the wind turbines are approved by the corresponding municipality (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) 2014).

In this report simplifications, based on the area usage and certain buffer distances, are used to determine suitable areas for wind turbines, disregarding the areas profitability. The area determination is based on a study from the Federal Environment Agency (Lütkehus et al. 2013), further referred to as the reference study. The reference study is chosen since it has the most detailed description from the selection in **Table 1**. If considered appropriate the values or areas used in the reference study are adjusted, therefore the result is not comparable to this report. This approach is found reasonable accurate, considering the large study area of this report and the input data resolutions. Further, determining the available area is not the focus of this report, but used as a basis for the wind turbine placement. As already shown in section 1.1.2 the in Germany available wind potential areas exceed the necessary area to meet the production in 2033. Therefore no sensitivity analysis is conducted on the excluded areas.

Only area relevant objects are excluded as potential wind turbine sites. That means, that line and point objects are just excluded if a buffer distance to them is defined. Very small streets and undefined building objects are therefore not excluded, which results in a slightly overestimated available wind turbine area.

Figure 8 shows the conducted steps to determine the available wind turbine area. Bold printed words mark the names of the applied tools in ArcGIS. In the following a few peculiarities while working with ArcGIS are explained to give a better understanding of **Figure 8**. The Buffer- tool in ArcGIS gives as a result only objects which have been

[22] BimSchG (BGBl I 2013 p. 1943), BBauGB (BGBl I 2013 p. 1548), BNatSchG (BGBl I 2013 p. 3154), LuftVG (BGBl I 2013 p. 3154), FStrG (BGBl I 2013 p. 1388)
[23] LBO (state building regulation of every state)
[24] If more than three turbines are placed together. The environmental site assessment is defined in UVPG (BGBl I 2013 p. 2749)

buffered. Since not all objects to be excluded need a buffer distance, for example Flora-Fauna-Habitats, those objects have to be added afterwards by merging the buffer output with the original data. The specific simplification layers have been chosen as a response to various error messages. Also the conversion of the slope values to integer values is because of earlier error messages. As a final step to gain the result, the forest area is reduced by iteration until it fits to the reference study. Numbers in parenthesis show the number of layers to the respective theme.

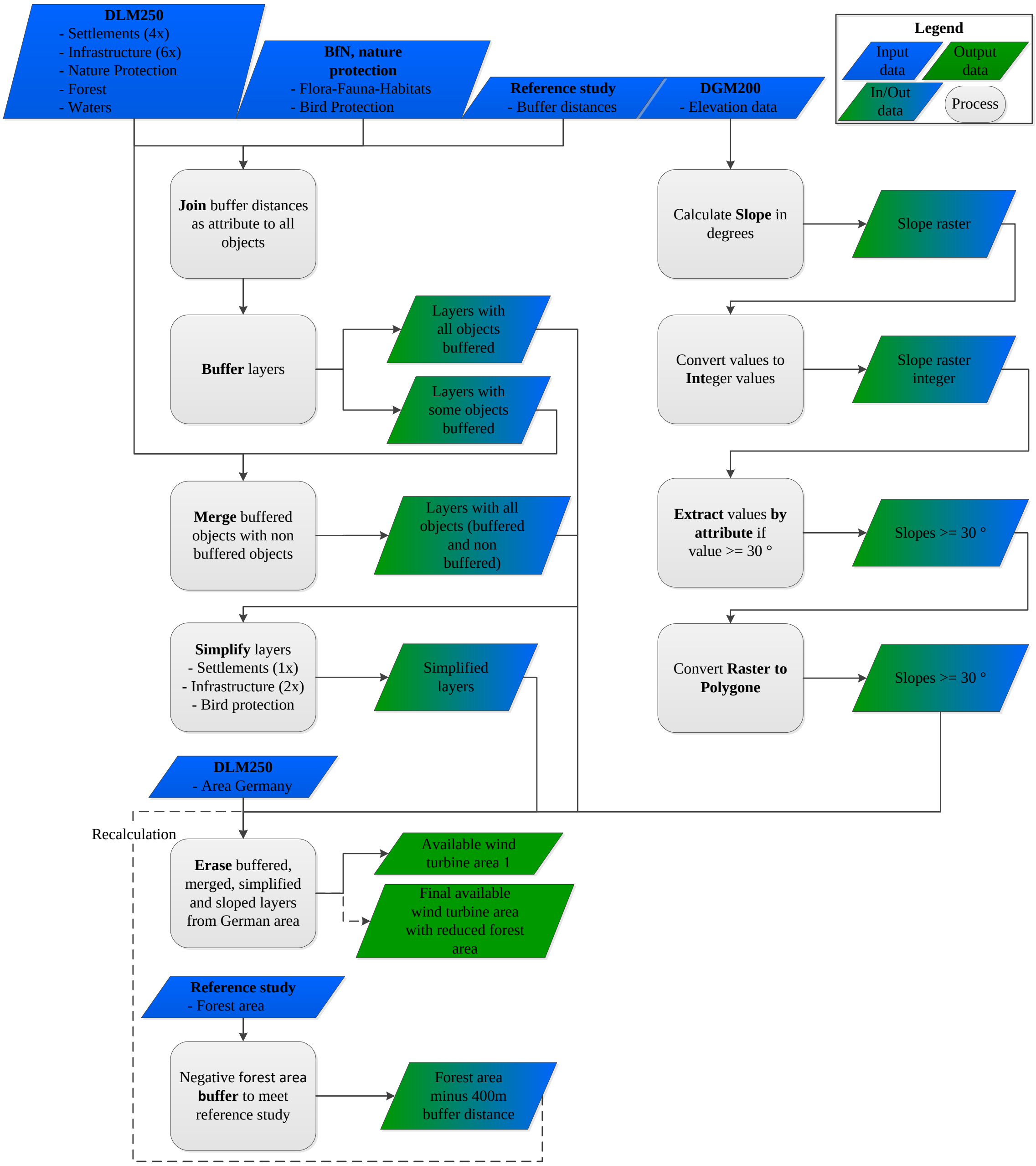


Figure 8: Detailed methodology for evaluating the available wind turbine area.

2.5.1 Settlement

Settlement areas are affected by wind turbines in many ways, among noise emissions, which is the only impact considered in this report. Acceptable noise emissions in differently used settlement areas are defined in (Bundesregierung 1998). The reference study converts these acceptable emissions into necessary buffer distances, based on the sound power of the high wind speed turbine given in **Table 3**. The reference study distinguished between acceptable emissions for the night- and daytime and uses a higher detailed dataset for settlement areas, than it is possible in this report. As a simplification only one buffer distance, the daytime distances, is applied in this report and shown in **Table 4**. Obviously this is a rather conservative assumption and more area than necessary is excluded. On the other hand no wind power curves for the daytime-mode are obtainable.

Table 4: Applied buffer distances from settlement areas (based on Lütkehus et al. 2013).

Type of settlement area from DLM250	Buffer distance from the wind turbine foundation
Industrial area	500 m
General settlement areas (for example residence areas)	1,400 m
Sport- and recreation area	2,000 m

In the DLM250 dataset the category sport- and recreation contains only theme parks and zoological gardens. Other recreation areas like holiday homes and campsites are not included, therefore the excluded area is too small.

2.5.2 Infrastructure

Mainly for legislative, technical and security reasons wind turbines have to have a certain distance to various infrastructure objects. The reference study lists and reviews the current legislation and applied practises and gives general buffer distances which are used in this report and shown in **Table 5**.

Table 5: Buffer distances to infrastructure objects (based on Lütkehus et al. 2013).

Type of infrastructure area from DLM250	Buffer distance from wind turbine foundation
Highway	100 m
Other road	80 m
Railway	250 m
Ropeway	300 m
International and regional airport	5,000 m
Small and private airport	1,760 m
Landline	120 m
Pipeline	120 m

2.5.3 Nature Protection

The areas shown in **Table 6** are excluded to account for nature protection. As mentioned at the beginning, potential wind turbine sites have to run through a detailed environmental assessment. Therefore the here excluded areas shall be seen as an indication. The exclusion is based on three different datasets shown in parenthesis in the table.

Table 6: Nature protection areas (based on Lütkehus et al. 2013).

Type of nature protection area (from dataset)	Buffer distance from wind turbine foundation
National park (DLM250)	200 m
Biosphere reserve, core- and care zone (DLM250)	None
Flora-Fauna-Habitat (BfN)	None
Bird protection areas (BfN)	200 m

Various other nature protection areas, for example bat protection areas and general protected landscape could not be excluded because of missing data.

2.5.4 Forest

30 per cent of Germany’s total area is covered by forests (Bundesamt für Kartographie und Geodäsie 2014b). With the height of the reference turbines, most forest areas can

technically be used for wind turbine production. The reference study argues, that depending on the usage of the forest, for example as recreation or noise protection forest, the forest shall or not be used for wind power production. Spatial data about the forest use could not be obtained and therefore it is decided to exclude all forest areas at first and reduce the excluded area subsequently until the figure from the reference study is met.

2.5.5 Waters

Any waters have been excluded from the potential wind turbine area. **Table 7** shows different types of waters and their respective buffer distances.

Table 7: Buffer distances of excluded waters (based on Lütkehus et al. 2013).

Type of water from DLM250	Buffer distance from wind turbine foundation
River and channel accessible to ships (inland waterway)	65 m
River and channel not accessible to ships	5 m
Lake	5 m

2.5.6 Steepness

Areas with a steepness of more than 30 degrees are excluded as available wind turbine area because, from a technical point of view, it is not possible to build wind turbines there. (Lütkehus et al. 2013)

2.5.7 Intermediate Result

Figure 9 shows the southern part of German as an example to illustrate overlaps and distribution of the area categories settlement, nature protection, forest and waters. This figure is not representative for Germany.

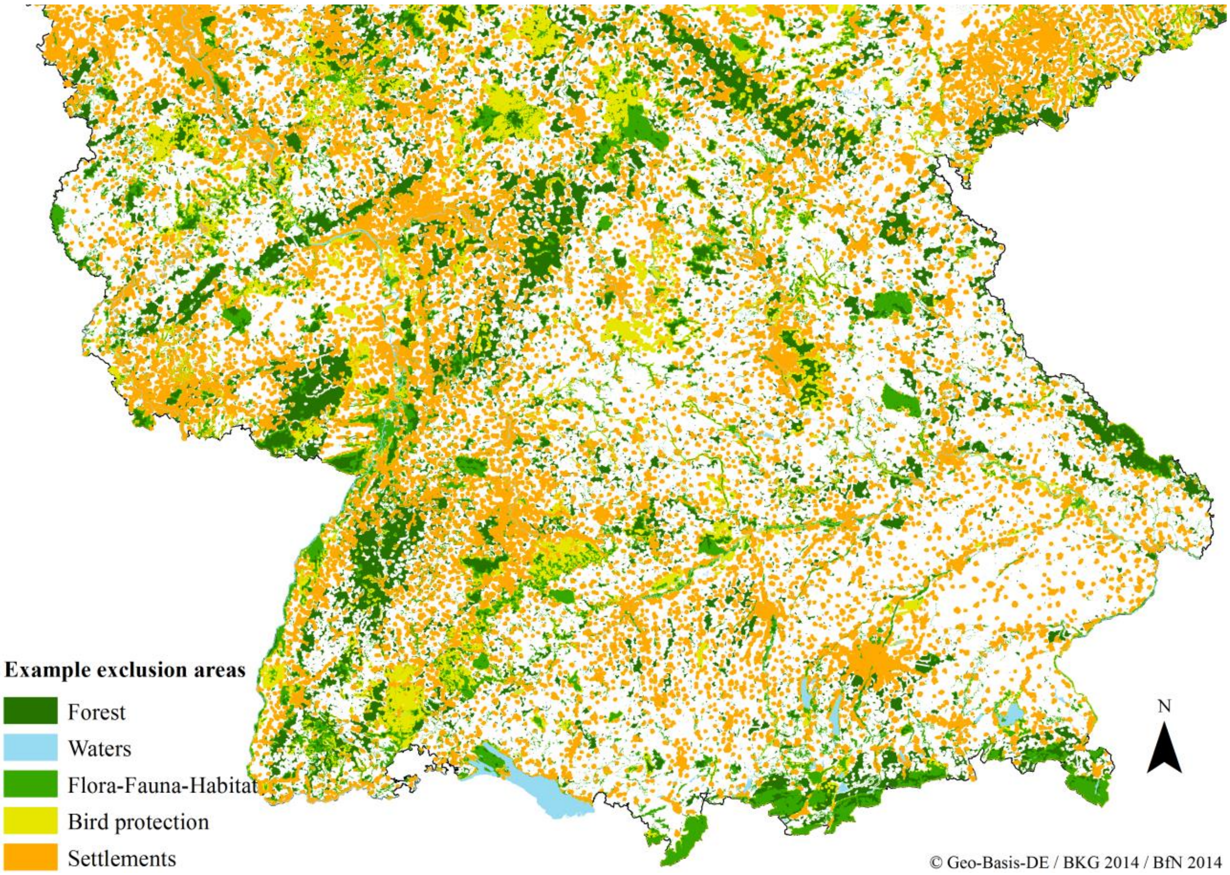


Figure 9: Example exclusion areas in the southern part of Germany.

After reducing the total area of Germany by the just described categories and their respective buffer zones **Figure 10** shows the final available wind turbine area for Germany. Available sites are marked orange.

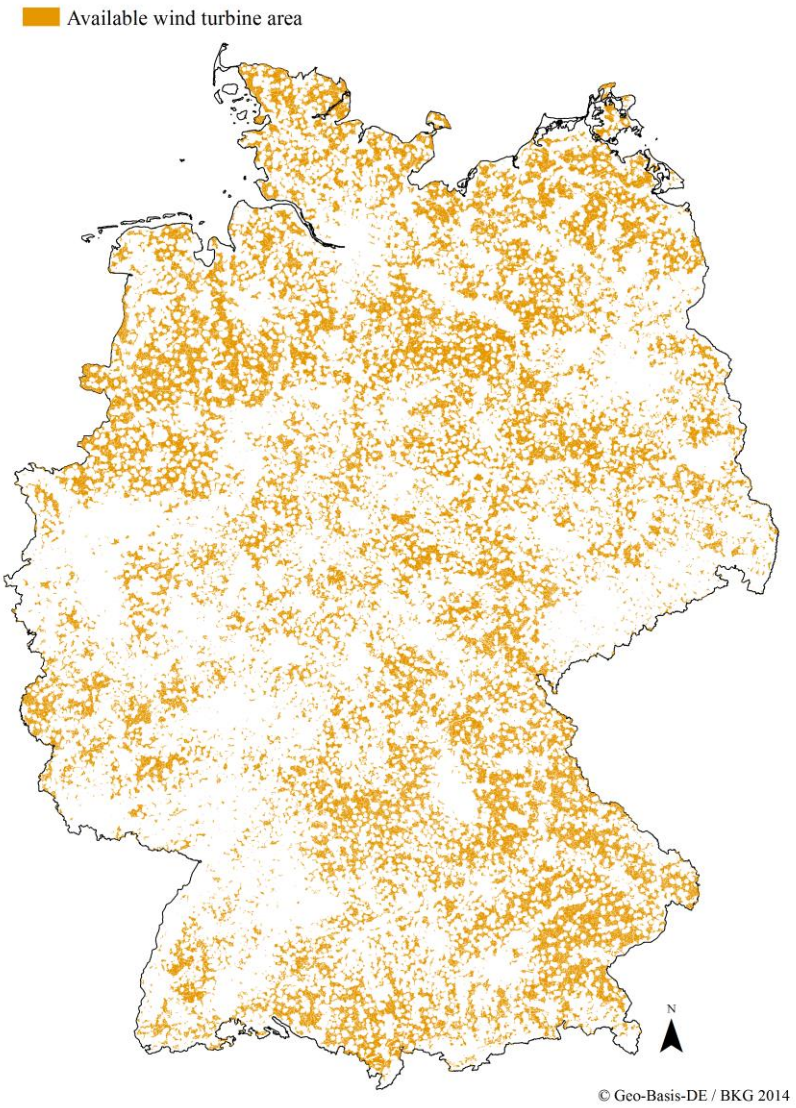


Figure 10: Available wind turbine area in Germany.

2.6 Placing the Wind Turbines

As a simplification, the location quality of a potential wind turbine site is only determined by its long term average annual wind speed. As described in section 0 this data is provided by DWD as 19-years historical average with a resolution of 1 km x 1 km. An historical average of 19- years is considered to be meaningful for the timeframe of this study. Depending if the average wind speed is higher or lower than 7.5 m/s either a high- or low-wind speed turbine is placed.

Figure 13 describes the conducted steps in ArcGIS to prepare the necessary placement data. The following explanations compliment **Figure 13**.

The DWD historical annual wind speed data in 80 m height is converted to 140 m to decide which turbine shall be placed on which raster cell. In such low heights the increase in wind speed is mainly determined by the surface roughness. The surface roughness is obtained by translating the CORINE land cover codes to roughness lengths (Silva et al. 2000). The height conversion is conducted with **Equation 1** (METEOTEST 2014), in which v_1 represents the original wind speed in 80 m height; h_1 the height of v_1; h_2 the height of v_2, here the hub height of 140 m; z_0 the roughness length and v_2 the wind speed at the height h_2. Heights are given in meters above ground and wind speeds in m/s.

$$v_2 = v_1 * \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Equation 1: Logarithmic wind formula.

In total 80 measurement stations, which provide hourly wind speed data, are public available for Germany. Four of them are offshore and therefore not relevant to this report, another four contain no data and another two are on the islands Helgoland and Norderney, which is beyond the study area since no other spatial data exists. Therefore 70 measurement stations are considered in this report.

The study area is divided in 70 sectors, to assign an hourly wind speed profile to each raster cell. This is done with the Thiessen Polygon Algorithm of ArcGIS. The algorithm assigns each raster cell to a point, here the weather station, to which it is closer than to any other weather station on the map (Delaunay 1934). The so created 70 groups are further called sectors and are seen in **Figure 11**.

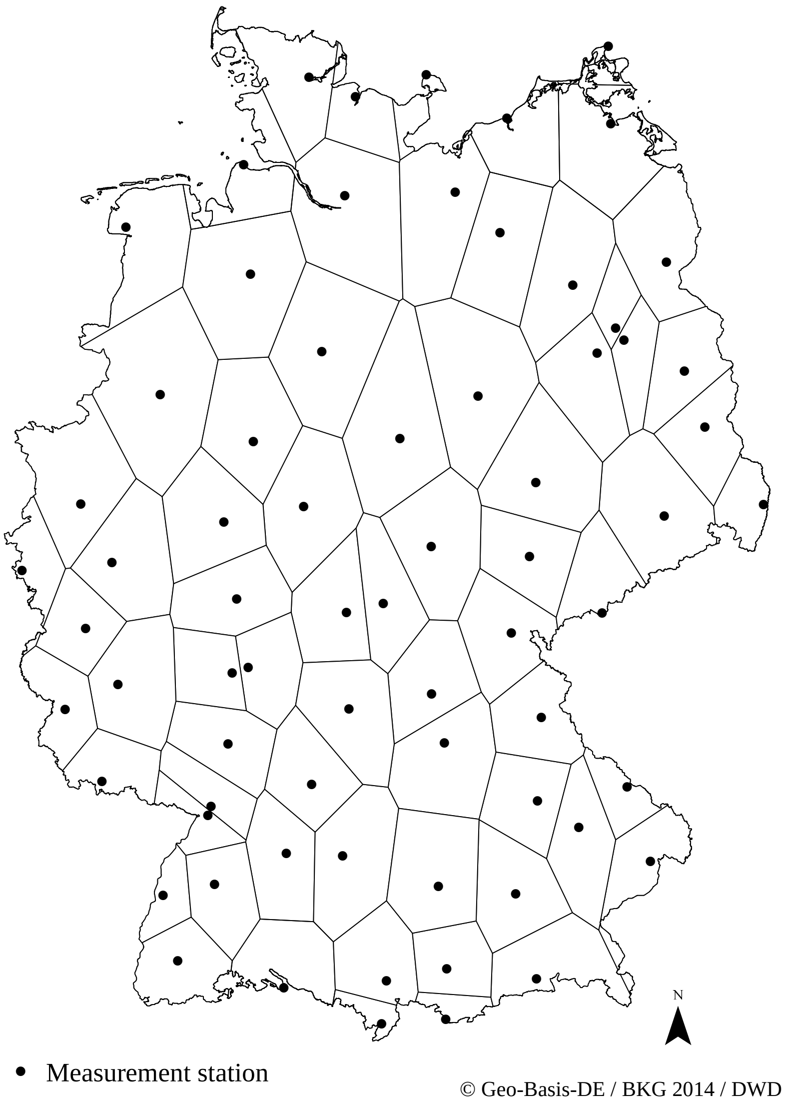


Figure 11: Germany divided in sectors based on 70 measurement stations.

Each sector has a high variance in wind speeds, so that taking the sector's average wind speed would warp the picture. In most sectors the average wind speed is much lower than the good wind sites.

This problem is resolved by first reducing and then categorising the wind speeds. Areas with an annual average wind speed lower than 5.7 m/s, which equals to 1600 full load running hours of the low wind speed turbine, are excluded, because it is not feasible to run a turbine here (BWE Bundesverband WindEnergie 2012). The calculation of this limit assumes a constant wind speed over the year and the available wind turbine area thereby reduced to 55,450 km².

Further the sectors are divided into, not necessarily spatial connected categories, based on wind speeds. The natural breaks algorithm (Jenks 1967) is used to build the categories. This algorithm seeks to minimise the variance within a group and to maximise the deviation to the average of the other groups (Jenks 1967). Therefore groups with very homogenous values originate, which is necessary here. One group has been slightly adjusted, so that the border is 7.5 m/s, to fit with the lower limit of the high wind speed turbine. **Table 8** shows the wind speed categories and their respective area. It can be seen that very good wind conditions are rare. In category 4 and 5, the high wind speed turbine is used.

Table 8: Wind speed categories with respective areas.

Wind speed category	Wind speed range	Area
Category 1	5.7 – 6.0 m/s	15,308 km²
Category 2	6.0 – 6.5 m/s	20,810 km²
Category 3	6.5 – 7.5 m/s	16,819 km²
Category 4	7.5 – 8.4 m/s	2,118 km²
Category 5	8.4 – 11.4 m/s	394 km²
Sum		55,450 km²

Figure 12 assembles the available wind turbine area, the 70 sectors and the five wind speed categories. Theoretical 350 combinations of sector and wind category are possible, but since not all sectors contain all wind speed categories just 261 combinations actually exist.

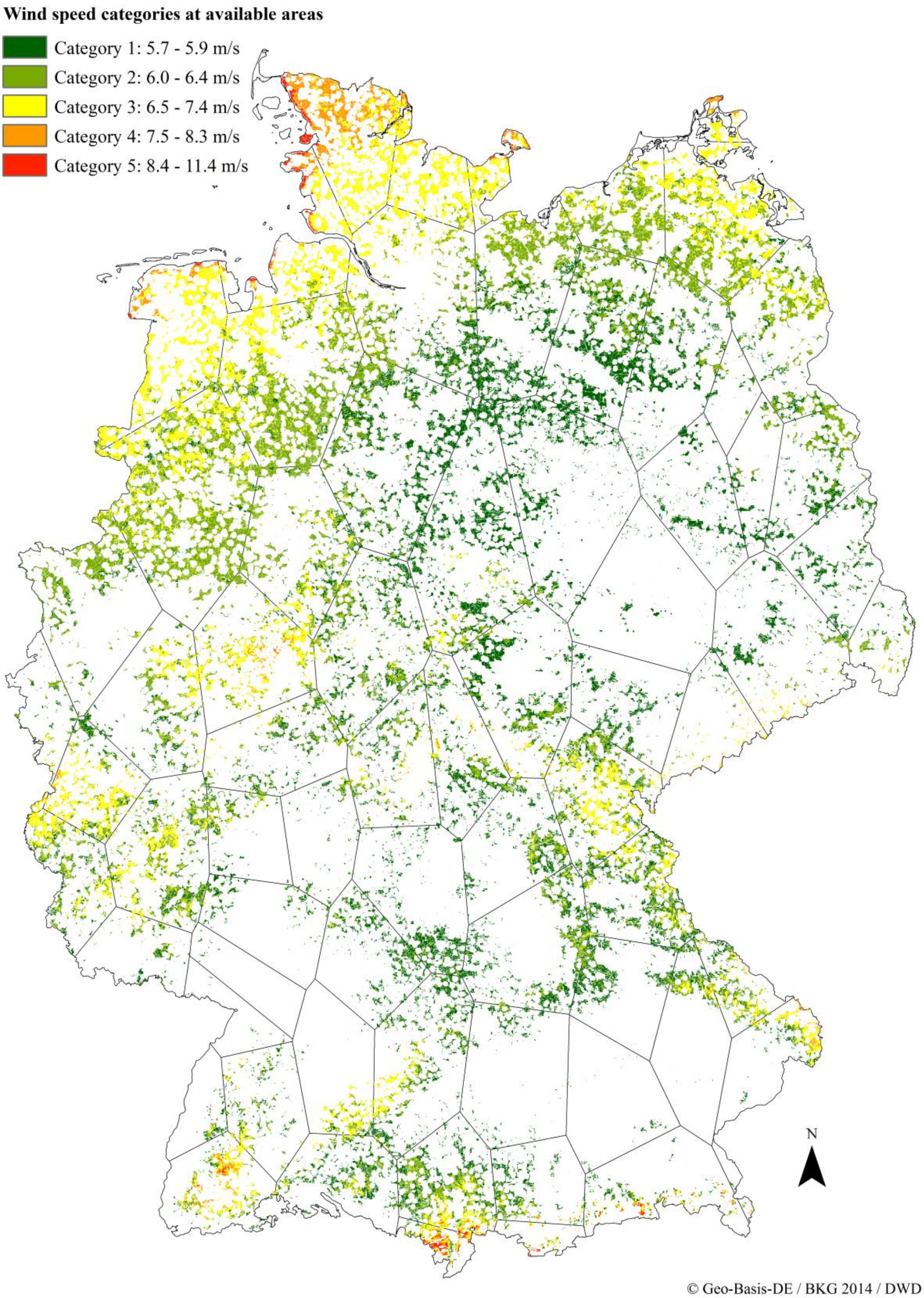
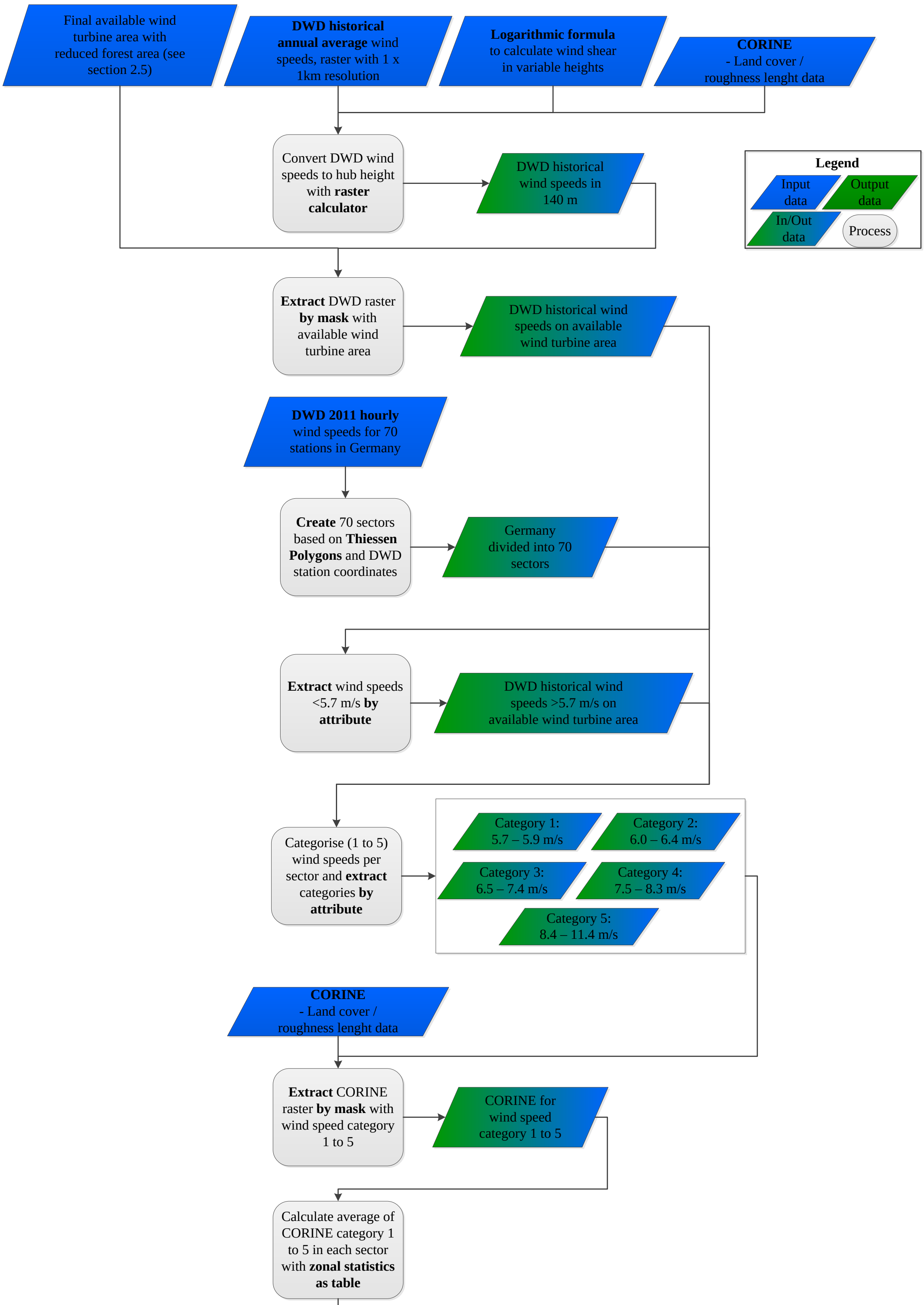


Figure 12: Available area, sectors and wind speed categories.

The roughness length for each raster cell in each category is extracted from the CORINE land cover data. The average is then taken for each combination of wind category and sector.

The result of this process is an Excel spreadsheet, further referred to as the placement spreadsheet, in which the sum of available area, the average roughness length of the surface and the annual average wind speed is assigned to each wind category in each sector. This table has 261 rows because of the number of existing combinations of wind category and sectors. An example of the table is given in **Figure 13**. This table is used as a basis for the wind turbine placement, according to the different scenarios.



Placement Excel spreadsheet

Sector ID	Category	Available area [m²]	Avg. roughness lenght [m]	Avg. wind speed [m/s]
4466	5	83,740,000	0,0613	9.4
4466	4	971,810,000	0,1003	7.7
4466	3	824,920,000	0,0886	7.2
...	...	...	...	...

Figure 13: Methodology of placing the wind turbines.

2.6.1 Distribution Scenarios

Based on literature research (BWE Bundesverband WindEnergie 2012; Lütkehus et al. 2013; Fürstenwerth 2013; Grothe & Schnieders 2011; Mono et al. 2014) and a conducted interview with two researchers from the Oeko- Institute (Bauknecht & Heinemann 2014), the following distribution scenarios for wind turbines are defined:

- Scenario 1 - Best wind sites.
  The underlying thought is to maximize the annual production. The wind turbines are placed on the highest long term average annual wind speed raster cells first.
- Scenario 2 - Even distribution.
  The turbines are placed evenly on the available wind turbine area, to prove the underlying thesis, that an even distribution reduces the fluctuation the most. Even by means of the same annual production on each square meter available wind turbine area. This can lead to the configuration, that in one sector the good wind spots are not fully used, but the worse are. This scenario seeks not to mirror a reality based even distribution, for example based on public acceptance. It seeks to show the maximal possible effect of even distributed wind turbine production. Therefore the turbines are consequent equally distributed.

Both scenarios produce 140 TWh per year disregarding the wind turbine distribution. This production is chosen according to the expected production around the year 2030 of the GGDP. Further information about the production allocation of the GGDP is given in section 1.1.1 and about its relevance in 2.1.

2.7 Calculating the Production Profiles

In both scenarios the annual production is the same to enable comparison. As mentioned above the annual production to be met is taken from the GGDP and equals to 140 TWh.

Figure 14 describes the applied method for the calculation of the sum production profile for scenario 1. First of all the Excel placement spreadsheet, the result from section 2.6, is sorted according to the average annual wind speed, starting with the highest. Then the number of maximal placeable turbines is calculated for each combination of sector and wind category, which equals to one row. For the two highest wind categories 4 and 5 the high wind speed turbine is placed, for the other categories the low wind speed turbine is used. The calculation uses the individual area need of the low or high wind speed turbine (see section 2.4).

The 70 wind profiles, measured in 10 m height above ground, for the year 2011 are used as a basis. The wind profiles are public available for the years 2007 to 2012. The year 2011 is chosen, since it is a rather average production year, both on the mainland and in shore regions (IWR 2012; Fürstenwerth 2013).

The hourly wind profiles are recalculated to the hub height of the respective turbine with **Equation 1** on page 46. The roughness length of the respective combination of the sector and the wind category is already calculated in section 2.6. The resulting 261 wind profiles are hourly multiplied with the respective wind production curve[25] and reduced by 15 per cent. 10 per cent of the reduction accounts for wake turbulences within a wind park, 2 per cent as fallout for maintenance and another 3 per cent for transmission losses (McKenna et al. 2014). It is considered that maintenance is normally conducted only once a year and therefore does not affect all hours. Since it is difficult to decide the time of the maintenance period, but the then decided period has a big influence, since the production is zero, it is decided that reducing every hour is a good simplification.

By summing up the hourly production profile the annual production per wind turbine in each combination of sector and wind category is calculated. This number is then multiplied with the maximal placeable number of wind turbines of the sector and wind category and equals to the respective total production.

The just described calculation is conducted for each of the 261 rows. The total production of each row is summed up until it reaches a production of 140 TWh, rounded to one turbine. The rows necessary to reach this production, here the first 38, are marked and their respective production profiles are summed up hourly to result in the total hourly production profile for scenario 1.

[25] As simplification, the wind power curve, which is normed to an air density of 1.225 kg/m³, is not recalculated to the air density at hub height.

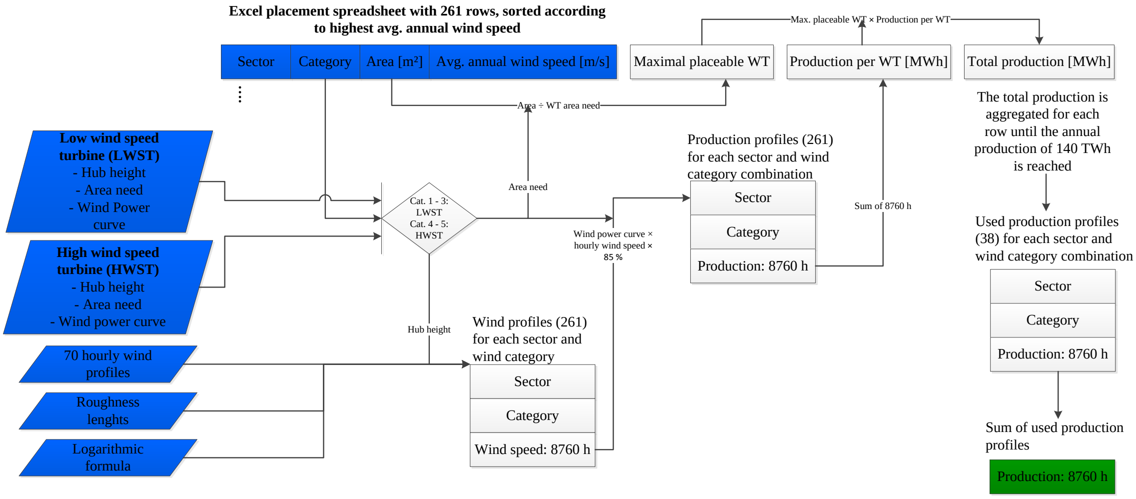


Figure 14: Calculation method for the production profile of scenario 1.

A different calculation method is used for scenario 2 and illustrated in **Figure 15**. Before running the actual model, a precalculation is conducted, in which the necessary number of turbines for all combinations of sector and wind category is determined.

Therefore an additional input, the production per specific area is required. This specific area factor is relevant for the consequent even distribution of the wind turbines, respectively their production. The factor is determined by dividing the production to be met, 140 TWh, by the available wind turbine area, 55,450 km² and equals to 0.0025 MWh/m² per year. The specific area factor is then multiplied with the available area of each sector and wind category combination, resulting in a necessary production per combination. The necessary production is recalculated to the number of turbines by dividing it with the production per turbine of the respective combination. From here on the number of necessary turbines replaces the number of maximal placeable turbines in **Figure 14** and the calculation proceeds as explained above, but the total production is not summed up, since it is already ensured by the specific area factor that 140 TWh are produced.

As a result 236 wind profiles are calculated and summed up. Theoretically 261 wind profiles would be used, but 26 areas are very small, so that already one turbine would exceed the determined necessary production. For that reason no turbine is placed.

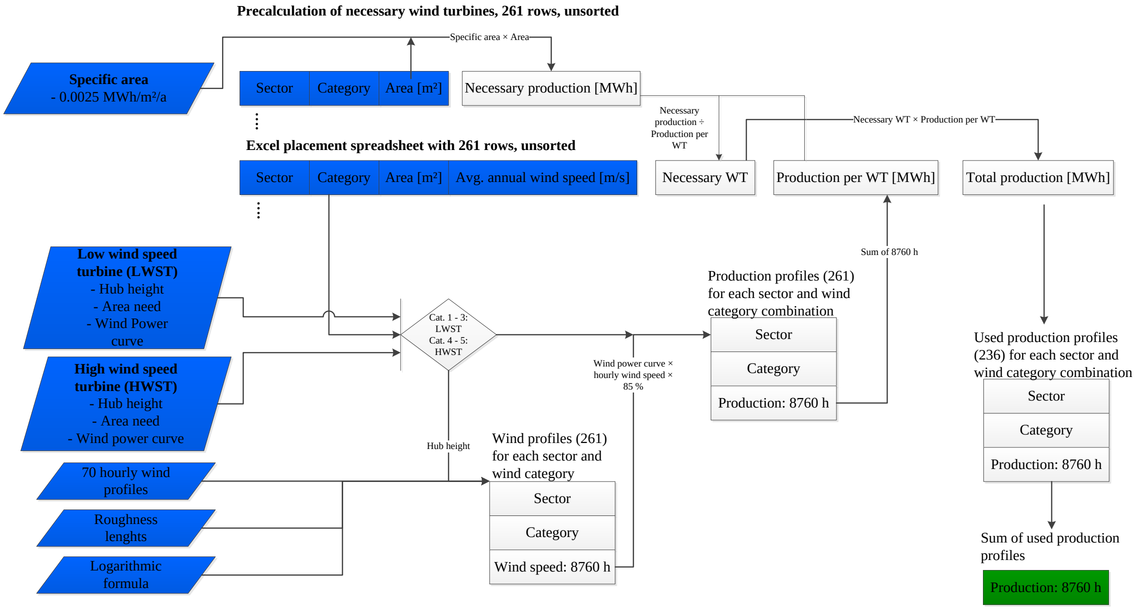


Figure 15: Calculation method for the production profile of scenario 2.

2.8 Calculating the Residual Loads

The residual load is defined to be the total load minus the wind turbine production. Since two production scenarios are calculated, also two residual loads are calculated.

The residual load is calculated on an hourly basis. To be consistent with the wind profiles, the total load profile for German in the year 2011 is obtained (European Network of Transmission System Operators (ENTSO-E) 2013). This profile just equals to 91% of the German consumption, the industry consumption is missing (European Network of Transmission System Operators (ENTSO-E) 2010). As a simplification the missing industry demand is modelled as a constant block over the year. The resulting profile is then slightly upscaled from 532.8 TWh/a to 535.4 TWh/a to match with the expected demand in 2033 from the GGDP.

3 Results

As a first step the available wind turbine placement area is determined from a planning perspective. This is done by ruling out areas with other, non-energy related land use, such as settlement-, infrastructure- and nature protection areas or for other reasons unsuitable areas. If necessary those areas are equipped with a buffer zone around them to account for visual influence and noise emissions from the wind turbines.

In a second step the wind turbines are placed according to the defined scenarios. In scenario 1 the turbines are placed according to the best wind site. In scenario 2 the turbines are placed evenly, so that every square meter available land has the same annual production. In both cases turbines are placed until an annual production of 140 TWh is reached.

Subsequently the hourly production of each scenario is calculated and aggregated for Germany. After subtracting the annual hourly production from the annual hourly demand, the resulting residual load curves are analysed according to the necessary flexibility.

For more detailed information it is suggested to look up **Figure 4** on page 28, which then refers to the detailed description of each step.

3.1 Available Wind Turbine Area

Germany has a total land area of 357,199 km². After excluding all areas unsuitable for wind turbines, as described in section 2.5, the initial available wind turbine area equals to 57,187 km². **Table 9** shows the excluded area by pooled categories. The figures do not consider overlaps of the categories. It is seen, that settlement areas, nature protection areas and forests limit the available area the most.

Compared to the reference study[26] the available wind turbine area found in this study is higher. The reference study found an area potential of 49,361 km² compared to 57,187 km² of this report. **Table 9** compares the results in more details. Afterwards it is

[26] The reference study is from the Federal Environment Agency (Lütkehus et al. 2013) and determines the available wind turbine area in Germany. For more information please see section 0.

evaluated, in regard to the in section 2.5 mentioned assumptions, where differences derive from and if values should be adjusted.

Table 9: Available area comparison to the reference study.

Area category	Excluded area of this study	In per cent of total excl. area	Excluded area of the reference study (figures from Lütkehus et al. 2013)
Settlement	335,159 km²	45.8 %	252,703 km²
Infrastructure	100,862 km²	13.8 %	111,079 km²
Nature Protection	156,371 km²	21.4 %	96,736 km²
Forest	105,680 km²	14.4 %	32,280 km²
Waters	33,259 km²	4.5 %	25,213 km²
Steepness	542 km²	0.1 %	unknown
Total excluded area, without overlaps	731,873 km²	100 %	518,011 km²
Resulting available area	57,187 km²		49,361 km²

In general it can be seen that the total limitation area of this report is higher than in the reference study, but the available area is greater. This indicates more overlaps among the categories.

More settlement areas are excluded in this report than in the reference study, because the distance of wind turbines to settlement areas is chosen to be the maximum buffer value evaluated by the reference study. It is chosen to stick with the maximum value, because only the louder daytime running mode of the turbines is modelled in this report. Further no conflict areas can be included and the higher buffer distance is partly seen as compensation for the rougher data input which does not contain small settlements and farmsteads.

Slightly less infrastructure area is excluded in this report. The major share of the discrepancy comes most likely from the different detailed data input. A minor share comes from necessary data simplification of the street and airport areas. An initial large discrepancy in the street layer could be reduced by changing the simplification type in the ArcGIS tool, this is elaborated in the appendix 8.1.

The excluded nature protection area in this report is greater than in the reference. Most likely additional nature protection areas have been marked in Germany since 2011, which was the data source year of the reference study. Therefore the found value is kept.

As already mentioned in section 2.5.4, no forest function data was available and therefore the whole forest area was excluded in a first step, which is obviously too much. It is found that 400 m of negative buffer distance reduces the forest area to the area of the reference study. This simplified approach affects all forest areas to the same extent, whereas more detailed data excludes only specific forest. The distribution of the excluded forest areas might therefore be warped. In general this implies that 70 per cent of the forest area is usable for wind power production. As a direct result, the available wind turbine area increases.

The data input for waters is considered to be good and the found value is therefore kept. This is supported by a fairly close value of the reference study.

The steepness input data is of a high resolution and the result is considered to be good. Also the excluded areas are reasonable distributed. No comparison to the reference study is possible because the value is not shown separately. **Table 10** shows the adjustment of the exclusion areas as discussed above and the finally used available wind turbine area. As it can be seen, the available wind turbine area increases and the excluded area decreases.

Table 10: Adjusted excluded area and finally used available wind turbine area.

Area category	Adjusted excluded area	Former value
Settlement	335,159 km²	No change
Infrastructure	100,862 km²	No change
Nature Protection	156,371 km²	No change
Forest	31,864 km²	105,680 km²
Waters	33,259 km²	No change
Steepness	542 km²	No change
Total excluded area, without overlaps	658,057 km²	731,873 km²
Final available wind turbine area	**81,184 km²**	57,187 km²

In general this determined land area has to be seen within the limitations of this report. In practise the area is probably lower, for example due to acceptance problems. Further the data input categories are rather general and as mentioned at the beginning, each possible wind turbine site has to pass an environmental assessment. The here found values can therefore not directly be transferred to a specific site, but give a good evaluation of the total area potential on a larger scale.

3.2 Wind Turbine Placement

After the available area is set, the wind turbines are placed on the area according to two scenarios, as described in section 2.6. In scenario 1, the best wind sites scenario, the turbines are placed according to the long term average wind speed, starting with the highest. In scenario 2, the even distribution scenario, the turbines are placed evenly, so that each square meter of available area has the same annual production.

Figure 16 represents the distribution of the wind turbines in scenario 1 within each sector. The used wind speed categories are defined according to the wind speeds in **Table 8**. It is seen, that only the high wind speed categories 4 and 5 need to be used to produce the target of 140 TWh per year. Therefore only high wind speed turbines are placed in scenario 1. The major share of the turbines is placed along the German coast line in the North, followed by the Alpine foothills in the South and a minor number in the Central German Uplands in the Middle of Germany as well as in the Ore Mountains in the East.

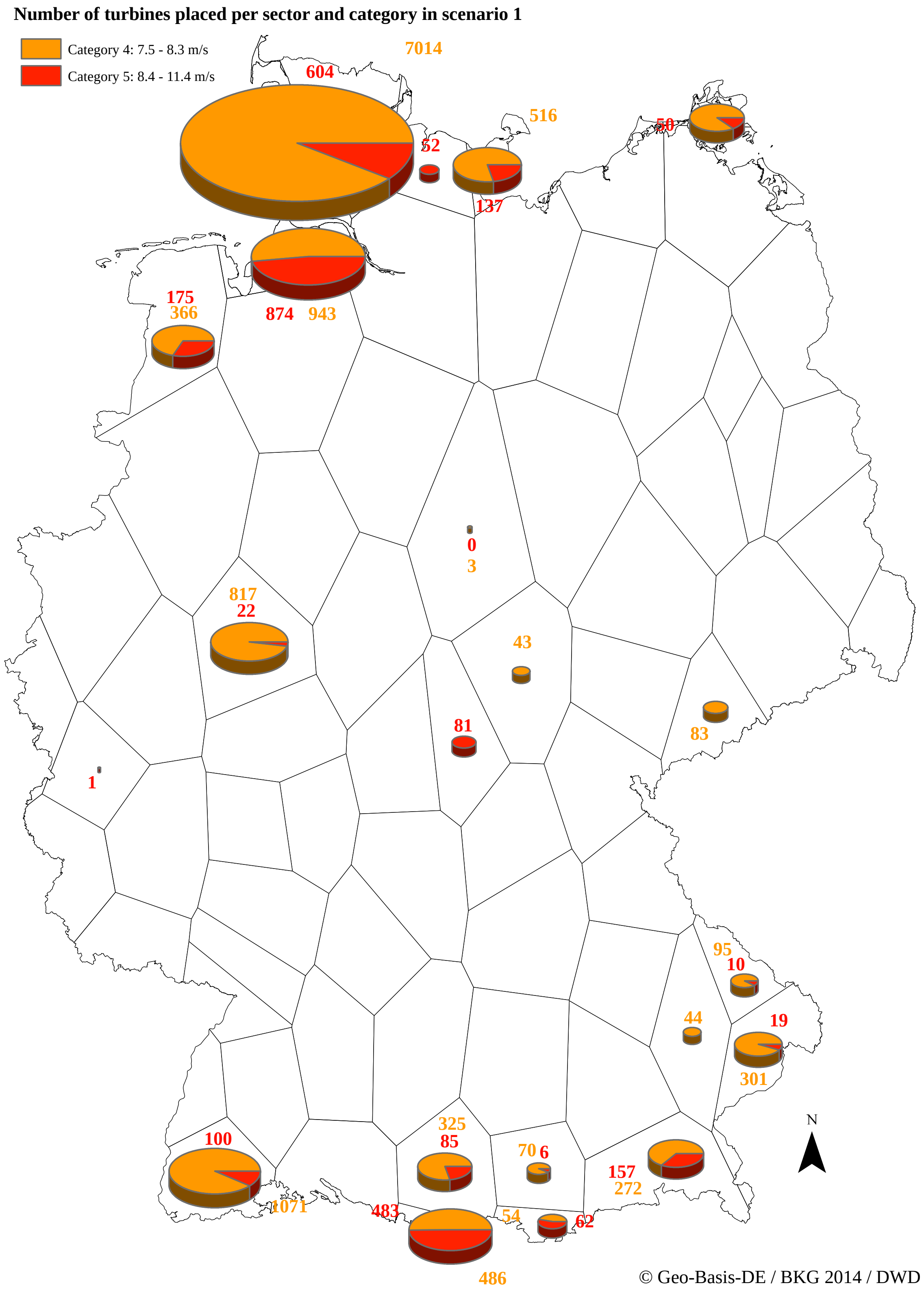


Figure 16: Number of turbines placed for each sector and wind speed category according to scenario 1.

Figure 17 represents the distribution of the wind turbines in scenario 2. It can be seen, that wind turbines are placed in every sector and in all of the five wind categories. Further the figure shows, that the distribution of the turbines over the sectors is similar to the distribution of the wind speed categories and the available area over the sectors, as it was shown in **Figure 12**.

Number of turbines placed per sector and category in scenario 2

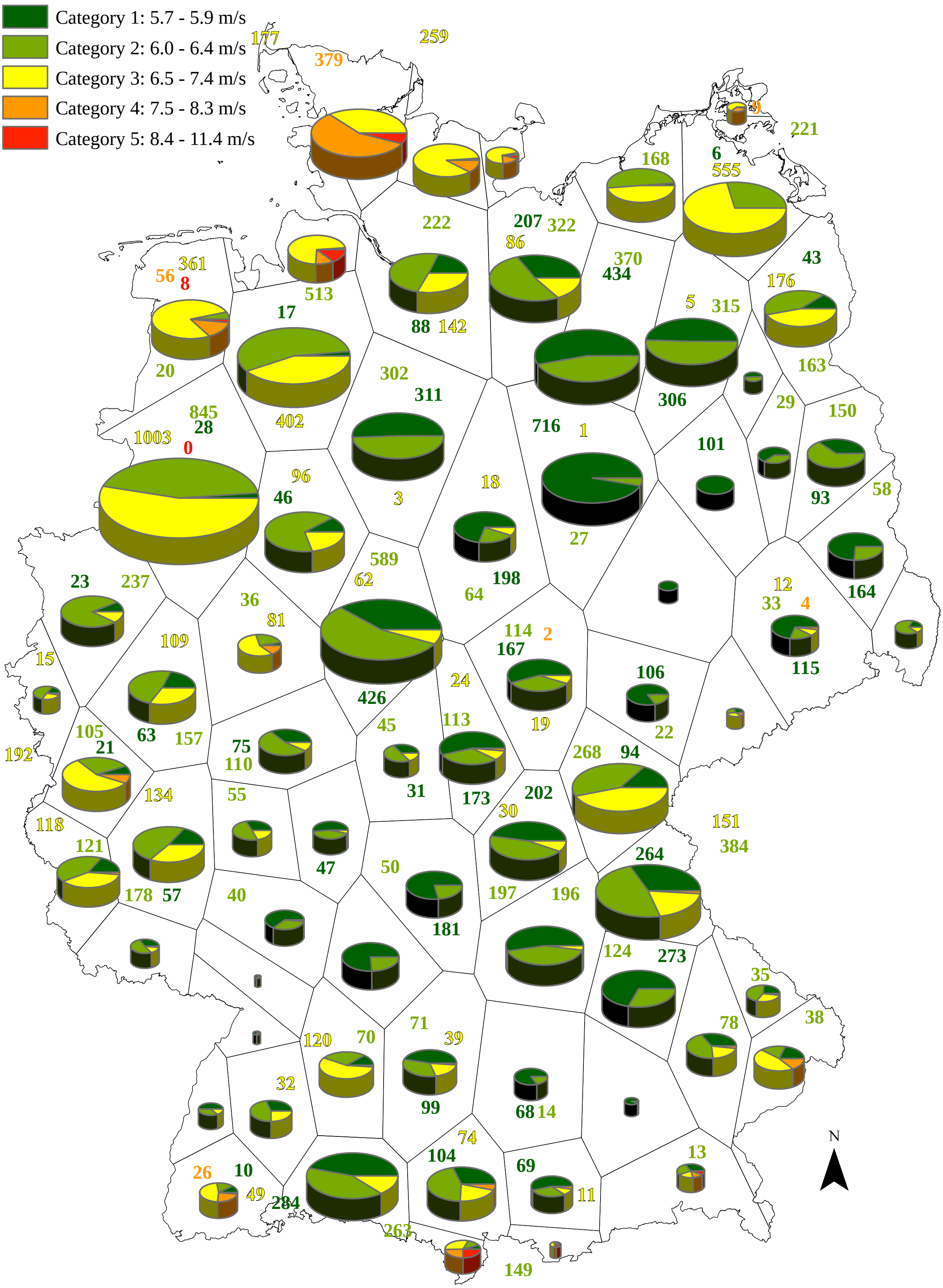


Figure 17: Number of turbines placed for each sector and wind speed category according to scenario 2.

3.3 Production Profiles

In the previous steps the wind turbines are distributed to the available area according to two different scenarios. In scenario 1 just the best wind sites, mainly in the North and some in the South are used. In scenario 2 the wind turbines are distributed evenly, so that each square meter available area has the same annual production. In this section the production profiles of the two scenarios are calculated, based on 70 different hourly wind speed measurements as it is described in section 2.7.

Table 11 summarises the key results. It is found, that mainly low wind speed turbines (LWSTs) are installed in scenario 2, which makes sense, since the wind categories 1 to 3 prevail in the available area. In total, more wind turbines are installed in scenario 2 and the installed capacity is 20 per cent higher than in scenario 1.

The total production is considered similar, the existing difference comes from rounding to one wind turbine.

Because of the utilisation of only very good wind sites, the wind turbines in scenario 1 reach higher full load hours. In 2011 the existing wind turbine mix in Germany reached 1,700 full load running hours (Pfaffel et al. 2011). Therefore the 2,145 full load running hours of scenario 2 seem to be in the right range, considering the in this report applied larger generators, higher hub heights and larger rotor diameters as the average in 2011.

The maximal peak production in scenario 2 is higher than in scenario 1. This seems to be contrary to the thesis, that a distributed wind turbine placement produces a smoother profile. The higher peak originates from the higher installed capacity. In relation to the installed capacity it is seen, that the peak production in scenario 2 reaches just 78 per cent of the installed capacity compared to 84 per cent in scenario 1. Relatively seen, this is a first indication for a smoother production profile of scenario 2.

Table 11: Production profile analysis of scenario 1 and 2.

	Scenario 1	Scenario 2
High wind speed turbine	15,757	835
Low wind speed turbine	0	20,840
Installed capacity [GW]	52	65
Total production [TWh/a]	139.99	140.02
Full load running hours [h]	2,692	2,145
Maximal production [MW]	43,646	50,882
Max [% of capacity]	84%	78%
Minimal production [MW]	767	834
Standard deviation [MW]	9,646	11,035
Std. deviation [% of capacity]	19%	17%

The minimal production is higher in scenario 2 because of the higher installed capacity, but also because less wind calms affect the production since the geographical distribution is greater. As it is pointed out in section 0, the wind speed correlation decreases with an increasing distance between the measurement points.

Figure 18 and **Figure 19** show the production profiles for both scenarios in the first week of April and the first week of December. In this segment of the production profiles it is seen that the general production trend is similar, but scenario 2 seems to have less local minima and maxima, which makes it smoother.

The standard deviation is used as an indicator to analyse the whole production profile. It shows how close the investigated values are grouped around the expected value, which is here the arithmetic mean. The smaller the standard deviation, the closer the values are grouped, which results in a smoother profile.

Table 11 shows, that the absolute standard deviation of scenario 2 is higher, because of more installed capacity. Compared in percentage of the capacity, the deviation of scenario 2 is 2 per cent lower. However, even if the production profile is relatively seen smoother, the absolute deviation is crucial for the electricity system.

The gap in the standard deviation between the scenarios was expected to be greater, because the deviation difference of their respective wind profiles is 6 per cent. **Figure 20** shows the normed wind profile for both scenarios in the first week of April. It is seen, that the wind speeds in scenario 1 are higher in general, which is reflected in the high full load running hours. Further the wind speed fluctuation seems to be smaller in scenario 2, which is supported by the greater difference in standard deviation.

There is no visible delay in wind peaks or calms between the two scenarios. Most likely this is because the dominating wind direction in Germany is West. Since the extent of Germany in West East direction is about 600 km a correlation of wind speeds is still possible. Also due to the distribution of the wind turbines in scenario 2, uncorrelated wind speeds are averaged out.

Possible reasons for a great difference in the standard deviation of the wind speeds but only a small difference in the standard deviation of the production profile could be that the high wind speed turbine compensates the fluctuating wind speeds well. This seems meaningful since it is made for this high and fluctuating wind speed conditions. Another reason could be that the low wind speed turbine does not fit well to the applied wind profiles.

In any case the effect of the spatial distribution on the production profile cannot be determined because it is warped due to the use of different wind turbines in the two scenarios. To answer this sub research question an additional analysis is conducted in which the same wind turbine placed in all wind conditions.

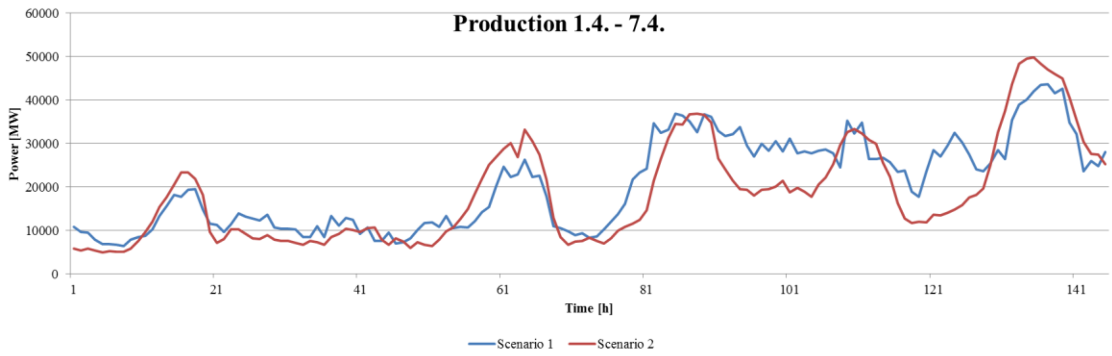


Figure 18: Production profile for both scenarios in April.

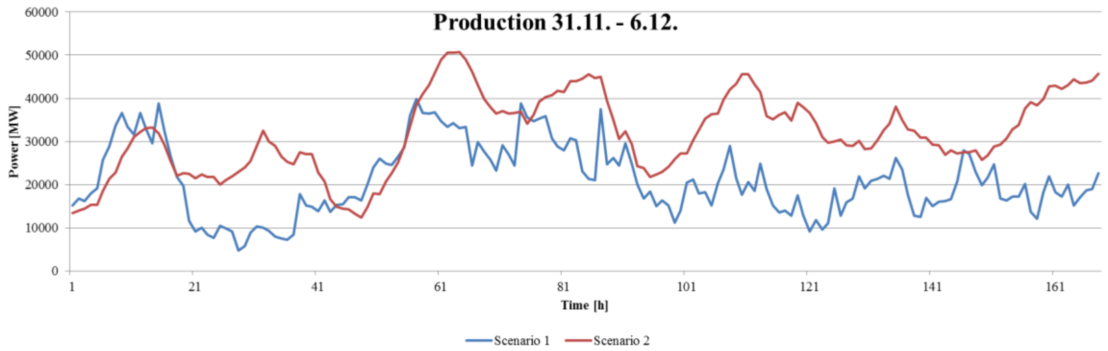


Figure 19: Production profile for both scenarios in December.

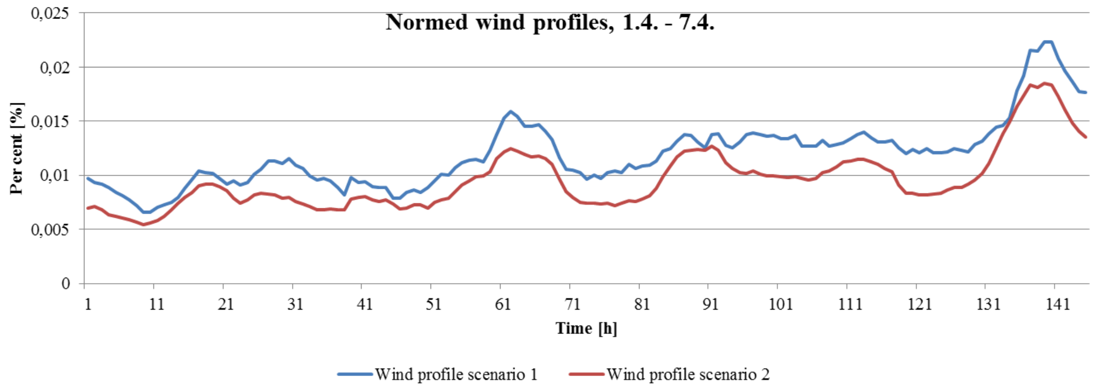


Figure 20: Normed wind profile April for scenario 1 and 2.

3.3.1 The Spatial Distribution Effect

In the previous analysis two reference turbines are used, depending on the long term average wind speed. By comparing the two scenarios, of which scenario 2 contains a mixture of the two turbines, the effect of the spatial distribution of the wind turbines cannot clearly be determined and the sub research question cannot be answered finally. Therefore an additional analysis of the two scenarios with only one wind turbine at choice is conducted.

The chosen turbine is the Enercon E-92 with a 2.35 MW generator, a hub height of 108 m and a rotor diameter of 92 m (ENERCON GmbH 2013). The turbine has a specific area of 2.83 m²/kW and can therefore be categorised between the high and low wind speed turbine, with a clear tendency to the high wind speed turbine (see **Table 3** for comparison). Again, due to difficulties to obtain the wind power curves of different wind turbines the Enercon E-92 was the best possible choice.

Table 12 summarises the key figures for the alternative scenarios 1a and 2a in which just one turbine type is applied. Compared to the scenario 1 and 2 it is seen, that more turbines have to be installed in scenario 1a and 2a, since the capacity of the Enercon E-92 is rather low. Scenario 1a reaches higher full load running hours and therefore less total capacity is necessary to reach the target production of 140 TWh. The chosen turbine in scenario 1 was therefore not the optimal fitting for the used wind profiles. In scenario 2a the number of turbines increases along with the capacity, both is not peculiar since the Enercon E-92 is rather made for high wind speeds. Due to the smaller rotor diameter more turbines can be placed on the same area and no spatial limits are reached.

The absolute maximum production increases in scenario 2a compared to scenario 2, due to the higher installed capacity. Especially interesting is, that the maximal peak production in relation to the installed capacity is 4 per cent lower than in scenario 2, which indicates a smoother profile. The higher number of turbines installed does not average out the peaks since the turbines are installed on the same spots with the same profiles. For scenario 1 and 1a the maximal peak in relation to the capacity is constant.

Especially interesting is that the relative standard deviation stays constant in scenario 1 and 1a but decreases by 2 per cent from scenario 2 to 2a. This leads to a doubling of difference in relative standard deviation between the scenarios. The production profile of scenario 2a became relatively seen smoother, compared to scenario 2.

Table 12: Production profile analysis of scenario 1a and 2a (same turbine for all wind categories).

	Scenario 1a	Scenario 2a
Wind turbines	20,313	34,642
Installed capacity [GW]	48	81
Total production [TWh/a]	139.99	139.97
Full load running hours [h]	2,933	1,719
Maximal production [MW]	39,939	60,517
Max [% of capacity]	84%	74%
Minimal production [MW]	873	723
Standard deviation [MW]	9.036	12.207
Std. deviation [% of capacity]	19%	15%

It can therefore be concluded, that the spatial distribution of wind turbines has a positive effect on the standard deviation, measured in relation to the installed capacity. Nevertheless, crucial for the system is the value of the absolute standard deviation. It is seen that the effect of the higher installed capacity in the distributed scenario surpasses the distribution effect. Therefore the absolute standard deviation of scenario 2a is 3,171 MW higher than in scenario 1a.

By using a turbine adapted to low wind speeds for scenario 2a, as it is done in scenario 2, the difference in absolute standard deviation is reduced, because the necessary installed capacity is reduced as well. On the other hand the relative standard deviation increases, because the low wind speed turbine can utilize the highest wind speed quantiles - the peaks. Due to the smaller rotor diameter the Enercon E-92 is not affected by these peaks.

3.4 Residual Load Profiles

According to the placement scenarios 1 and 2, the wind turbines are distributed differently over Germany and two different production curves are calculated in the previous sections. In this section two hourly residual curves are calculated, by subtracting the production profiles from the demand profile, as described in section 2.8. The used total load profile is thereby from 2011, but upscaled to the expected demand in 2030, as also described in section 2.8. The residual load profiles are analysed in regard to the necessary flexibility in the system.

In this section it is referred back to the analysis of the production profiles conducted in section 3.3. In **Table 11** the key results of the production profile analysis are presented.

As it is seen in **Table 13** the total residual load is similar in both scenarios and equals to the total load minus the respective wind production. That implies, that in no hour the production exceeds the demand. This is also shown by the positive minimal residual load in both scenarios.

The maximal residual load, which represents the flexibility capacity to be installed, is similar in both scenarios. This indicates that the production profile of scenario 2, or at least its peak production, suits better to the demand profile. The peak production of scenario 2 is 7,236 MW higher than the peak production in scenario 1.

Since the minimal residual load is positive, it equals to what the flexibility options have to provide as so called must-run capacity as a band for all hours of the year. Certainly other renewable production technologies like photovoltaic reduce this must run capacity in the real world electricity system.

The absolute standard deviation of the residual load in scenario 2 is higher than in scenario 1. Due to the higher production peaks of scenario 2 this is not surprising. By comparing the difference in absolute standard deviation of the production profiles, which is 1,389 MW and the difference in absolute standard deviation of the residual load, which is 320 MW, it is seen, that the gap becomes smaller. That shows, that the production profile of scenario 2 fits better to the load profile.

Table 13: Residual load analysis of scenario 1 and 2.

	Scenario 1	Scenario 2
Total residual load [TWh/a]	395.40	395.38
Maximal residual load [MW]	75,400	75,404
Minimal residual load [MW]	1,964	2,379
Standard deviation [MW]	12,974	13,294
Std. deviation [% of inst. capacity]	25%	20%
Average gradient (+ and -) [MWh/h]	2,789	2,347
Maximal gradient (+ and -) [MW/h]	18,962	15,103
Number of blocks of same sign	2,987	2,301
Largest block (+ and -) [MWh]	88,735	77,087

Even though it is found, that the same flexibility capacity is necessary in both scenarios, the characteristics of the flexibility have not yet been discussed. The hourly gradient analysis in **Table 13** shows how much more or less the installed capacity has to produce in one hour. In other words it represents the steepness or hourly change of the residual load curve.

It is seen, that the average gradient in scenario 2 is flatter and also the maximal gradient is lower, which supports the thesis of a better fitting production in scenario 2. In addition **Figure 21** shows, that groups of high positive or negative gradients occur more often in residual load curve 1. On the other hand smaller gradients and zero gradients occur more often in residual load curve 2. Due to this more often occurring smaller changes the residual load curve becomes smoother.

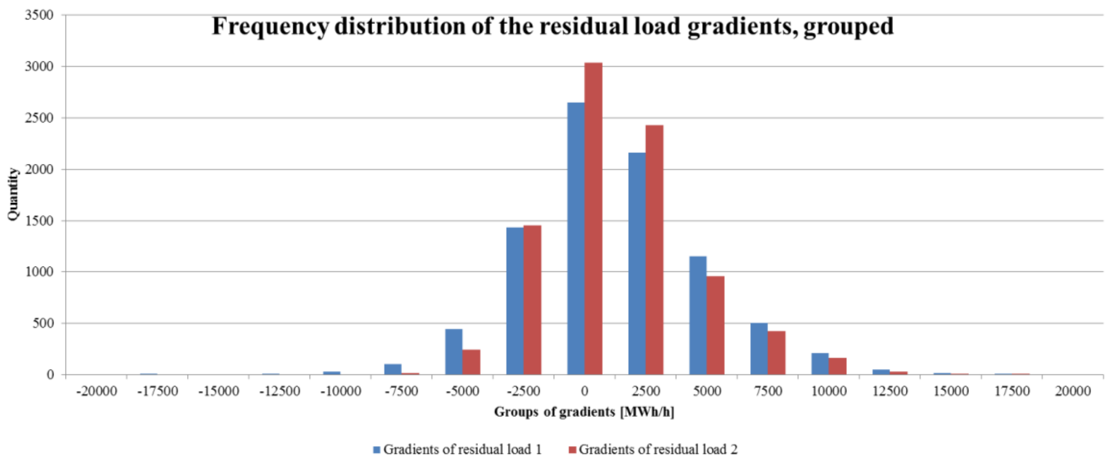


Figure 21: Frequency distribution of the residual load gradients.

Also important for the characteristics of the flexibility is how much continuous production[27] has to be provided maximally. The largest continuous block in residual load curve 1 is 88,735 MWh compared to 77,087 MWh in residual load curve 2.

In conclusion the spatial distribution of the wind turbine production influences the necessary flexibility in the system. The necessary capacity and its characteristics are shown in **Table 14**. The same flexibility capacity has to be installed in both scenarios to produce the residual load. In scenario 1 this flexibility has to provide a steeper maximal gradient, but also in general steeper gradients. In scenario 2 the maximal gradient is about 20 per cent and the average gradient about 16 per cent lower than in scenario 1. Furthermore the largest block of continuous necessary production is about 15 per cent higher than in scenario 2.

Even though the same flexibility capacity is necessary, the flexibility requirements in scenario 1 are higher.

Table 14: Necessary configuration for the flexibility.

	Scenario 1	Scenario 2
Necessary flexibility [MW]	75,400	75,404
Average gradient (+ and -) [MWh/h]	2,789	2,347
Maximal gradient (+ and -) [MW/h]	18,962	15,103
Largest block (+ and -) [MWh]	88,735	77,087

[27] The term „continuous production“ describes consecutive hours of the same, positive or negative, production.

4 Discussion of the Results

The first result of this report is the available wind turbine area. The found area size of 81,184 km² might be lower in the real world, since not all area reducing factors, such as public acceptance and special species protection could be considered in this report. On the other hand, the noise reduced turbine mode is not applied in this report and rather conservative distance assumptions are made. The found available area is therefore considered a good evaluation of the total area potential in Germany. In practice, each site has to pass an environmental assessment before wind turbines are built.

The modelled scenarios in this report, the best wind sites and the even distribution, are chosen to show the maximal effect of the spatial distribution on the necessary flexibility and not to model realistic scenarios. For further research it would be interesting to examine a scenario in which the current political concepts are reflected. For example the individual wind production goals of the German federal states. Also interesting would be an optimisation within the mix of locations and turbines chosen, in order to decrease the fluctuation.

As expected more turbines have to be installed in the even distribution scenario, since also poor wind sites are used. This trend is consistent with other studies, but the increase of 25 per cent is not comparable to other studies, since the used scenario parameters, such as the definition of an even distribution or the annual production to be reached, are different.

In the two scenarios two different turbines are used, depending on the average wind speed of the potential site. It was found that the chosen turbines not only have an effect on the total necessary wind capacity and the average full load running hours, but also on the fluctuation of the production profile. Therefore, in future research, more than two reference turbines should be used. Further, the turbine placement shall not be determined by the average wind speed, but by the full load running hours of the respective turbines, this is further discusses in the alternative methodology section 1.

Unexpected is the result, that the even distribution scenario requires the same flexibility capacity than the best sites scenario. Initially the thesis was, that due to a smoother production profile of the even distribution scenario, less flexibility capacity is necessary in the system. This thesis is disproved, since the effect of more installed wind power capacity surpasses the smoothening effect of the spatial distribution. Other studies (Mono et al. 2014; Fürstenwerth 2013) neglect this effect, by comparing different scenarios according to their necessary flexibility gradients and correlation between sites, but not according to the absolute necessary flexibility capacity. However, seen relatively to the installed wind power capacity the even distribution scenario fluctuates less. Further the even distribution scenario fits, also absolutely seen, better to the load profile. As said, that results in the same necessary flexibility capacity, but with lower necessary average and maximal hourly gradients and with no need to install wind turbines at the best wind sites.

On the economic side it is assumed that the lower flexibility gradient requirements result in cheaper flexibility capacity, because options like demand side management can be used instead of fast responding power plants. On the other hand about 6,000 more wind turbines have to be build in the even distribution scenario. To finally calculate the wind turbine investment cost, the hub height, the rotor diameter and the generator size have to be considered, which is up to further research.

The distribution of the production in the respective peak hour of both scenarios is shown in **Figure 22**. It is seen, that in the best site scenario the very north sector accounts for 49 per cent of the total peak production. In the even distribution scenario the maximal production of one sector equals to 9 per cent of the total peak production. It is also seen that the production in the peak hour is way more distributed over all sectors, because the wind turbines are placed evenly. Therefore more grid capacity is necessary in the best site scenario to transport the production, at a transmission loss, to the load regions in the West and South of Germany, which is most likely advantageous for the even distribution scenario. However a detailed cost benefit calculation, which takes the necessary grid capacity and the number of turbines into account, is up to further research.

Considering the link between the electricity and the heat sector, the even distribution scenario might have an advantage since the production is more distributed and therefore less electrical grid capacity is necessary to transport production peaks to the heating demand. Nevertheless other renewable energy production technologies have to be considered to make a point.

By doing so, run-off river and biomass have a rather flat and predictable production profile compared to photovoltaic. Photovoltaic is similar intermittent to wind. That means, that greater peaks can occur, which would result in a greater necessary flexibility. The rather flat production goes along with the fossil fuel based must-run capacity and increases the minimal and maximal necessary flexibility capacity additionally. On the effect of spatial distributed production of wind and photovoltaic it is referred to (Mono et al. 2014).

A general disadvantage of the even distribution scenario is, that more land area is used for the wind turbines. This may trigger public acceptance issues.

Due to the larger area used in the even distribution scenario absolutely seen more people are affected visually by fewer wind turbines. In the best site scenario less people are affected, but by a larger number of turbines. Further, the best wind sites in the Middle and South part of Germany are in the mountainside, which serves besides the environmental, also recreation and activity purposes. Also those sites are normally not connected to infrastructure like roads or transmission lines, but both is necessary to build and run the turbines. Therefore the best sites scenario might be opposed by land use conflicts as well as difficulties within the grid connection process.

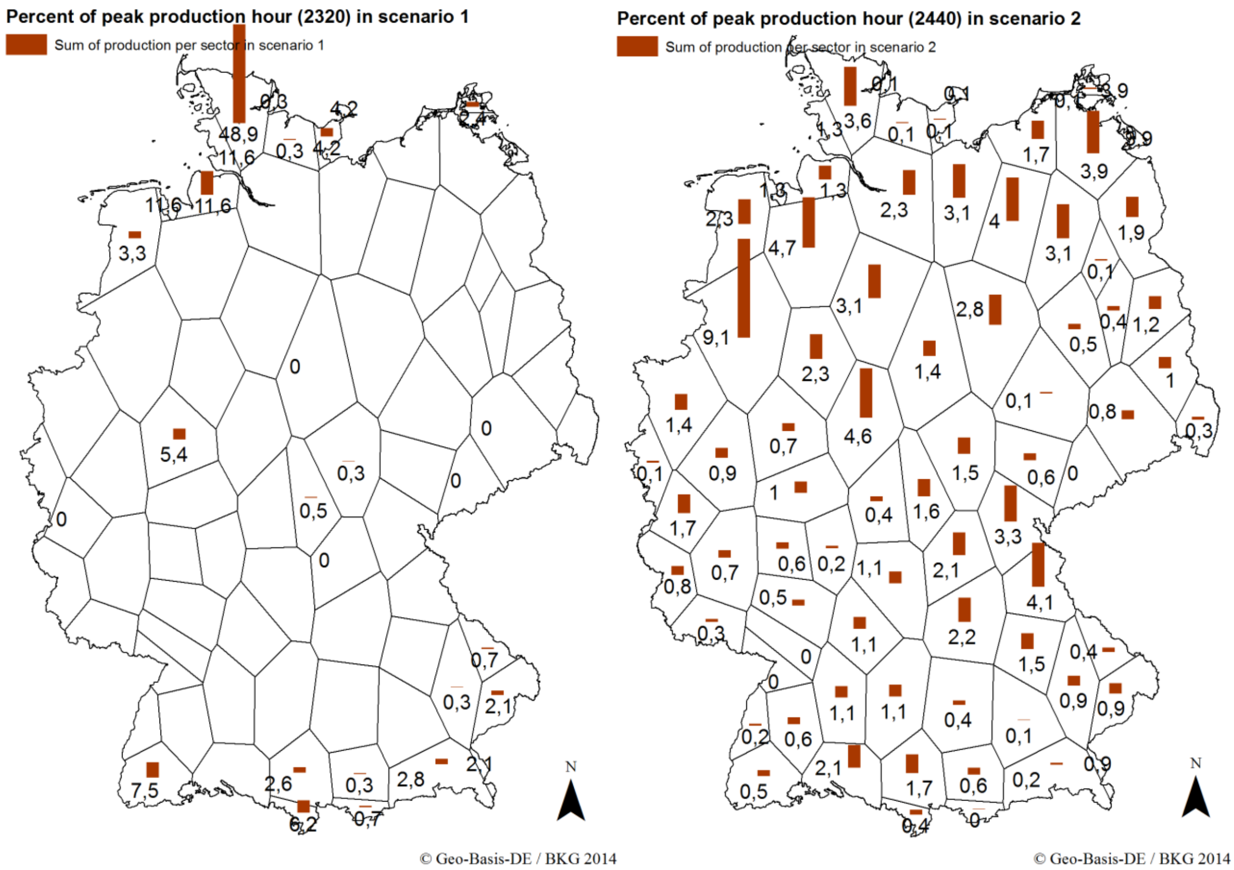


Figure 22: Distribution of the peak production per sector in scenario 1 and 2, with respective percentages of the peak.

5 Conclusion

The European Union as well as it’s member state Germany aim to reduce greenhouse gas emissions and thus limit global warming. One of the measurements to achieve this goal is to increase the share of renewable energy in the electricity sector.

The German Grid Development Plan suggests onshore wind power as the main electricity producer in the year 2033. Based on historical development, current policies, an active discourse about renewable energy in Germany, and the spatial and wind potential it is expected that this high share of wind power is reached.

With a high share of onshore wind power, reinforced by photovoltaic, the intermittent electricity production increases, but integration is obligatory. Integration can be achieved through flexibility options, like storages and demand side management, or by smoothing the production curve. This leads to the research question of this report:

How does the spatial distribution of wind turbines affect the necessary flexibility in the future German electricity system?

The research is guided by the following sub- research questions:

- Where can turbines be located?
- Based on current studies: With which distribution scenarios can wind turbines be spatial distributed to the available area?
- How does the production profile change with different spatial distribution?
- Taking the demand into account: How does that influence the necessary flexibility in the system?

The methodology developed to answer the research question contains the following main steps.

First, the area on which wind turbines can be placed is determined from a planning perspective using a geographical information system. This is done by ruling out areas with other, non-energy related land use, such as settlement-, infrastructure- and nature protection areas or for other reasons unsuitable areas. Any kind of social acceptance issues are not considered in this report.

In a second step, two spatial wind turbine distribution scenarios, the best wind sites scenario (scenario 1) and even distribution scenario (scenario 2) are determined. In scenario 1 the turbines are placed according to the best wind site. In scenario 2 the turbines are placed evenly within the available wind turbine area. In both scenarios turbines are placed until an annual production of 140 TWh is reached.

Subsequently the hourly production of each scenario is calculated, based on 70 wind profiles from weather stations all over Germany, and aggregated for Germany. After subtracting the hourly production from the hourly demand, the resulting residual load curves are analysed, according to the capacity and configuration of the necessary flexibility.

By deploying the just described methodology the following results are achieved.

→ In Germany about 25 per cent of the total area can be used to place wind turbines.

The two determined scenarios are chosen to be extreme in order to show the maximal effect of the spatial distribution. In scenario 1, the best site scenario, the turbines are placed according to the long term annual wind speeds, starting at the location of highest wind speed, until the production of 140 TWh is reached. In scenario 2, the even distribution scenario, the turbines are placed evenly all over Germany. The even distribution is ensured by the same production per square meter of available wind turbine area. Also in scenario 2 an annual production of 140 TWh is achieved.

→ In the even distribution scenario about 6,000 turbines have to be installed more than in the best wind sites scenario.

After placing the turbines, the aggregated production profiles are calculated for each scenario. Seen relatively to the installed capacity, scenario 2 has a lower standard deviation and therefore a smoother production, because of the spatial distribution. But since more turbine capacity has to be installed in scenario 2, the absolute maxima and the absolute standard deviation is higher than in scenario 1.

→ The effect of the higher installed capacity in the even distribution scenario, surpasses the smoothing effect of the distributed placement.

Subsequently two residual load curves have been calculated, by subtracting the production profiles from the hourly demand profile. Thereby it is found, that the production curve of scenario 2 fits better to the demand curve, which results in a smoother residual load curve. Nevertheless the same flexibility capacity is necessary in both scenarios, with the difference, that the average and maximal gradients to be provided by the flexibility in scenario 2 are lower.

→ The residual load curve of the even distribution scenario is smoother, which results in lower flexibility gradients but the same flexibility capacity.

Even though many aspects, such as social acceptance and economic consideration are not included in this report, they are briefly discussed. Most likely the available wind turbine area calculated in this study may be overestimated, because of public acceptance issues. That means that scenario 2 needs an even higher share of the available area, which leaves less area for other usage. From an overall investment point of view it seems that two main factors are opposing. In scenario 1 less turbines have to be installed, because the turbines are placed on the best wind sites, but on the other hand, in scenario 2 less grid capacity is necessary due to an even distributed production.

Evaluating these two aspects would give an additional value to the topic of spatial distributed wind power production and is therefore suggested as further research topic.

The thesis of a general smoother production profile through an even distributed wind turbine scenario is disproved. However, distributed, less profitable wind sites, with various advantages are usable by providing the same flexibility capacity with lower gradients.

6 Alternative Methodological Approaches

The development of the described methodology was not only a straight forward approach but also shaped by errors. In this section three dead end approaches are discussed.

For the hourly wind speed data two datasets have been obtained:

a) Hourly wind speed raster data, based on the reanalysis data from DWD, with a 2.8 km x 2.8 km resolution in 90 m and 150 m height

b) Hourly wind speed point measurements for 70 stations in 10 m height

Option a) was processed first. The data originates from the DWD weather forecast model COSMO-DE (Baldauf et al. 2011) for Germany and is provided as GRIB[28] data (GRIdded Binary) with wind speeds as vector components in 90 m and 150 m height and a rotated North Pole. The two height level datasets for Germany have a file size of about 14 GB. Four editing steps are necessary to use the data: First, the GRIB format has to be decoded and convert it to a more applicable file format. Second, the values of each raster have to be rotated to the geographical North Pole to match with all other spatial data. Third, the vector wind speed components have to be converted to resulting wind speeds. Fourth, each resulting wind speed has to be converted to the two hub heights of the reference turbine.

At the end it was not possible to rotate the amount of data without a special program, which was not provided by the DWD. Alternative and available solutions exist, but due to the timeframe of this study, it was not possible to grapple with these alternatives and option b) was considered more reliable and therefore applied.

[28] For detailed information, see http://www.wmo.int/pages/prog/www/WMOCodes/Guides/GRIB/GRIB1-Contents.html

Another crucial decision was the placement of the wind turbines. Again two options have been possible:

a) Detailed placing of each wind turbine in a designated raster cell with a python script

b) Placing wind turbines in averaged area in Excel

Option a) was processed first. A python script has been written to place the wind turbines on a result raster with a resolution of 100 m x 100 m. The python code uses the 70 wind profiles and converts them to each raster cell by using the cells roughness length etc. In contrast to the Excel solution, where different averages per sector and wind category are used approach a) is more detailed and accurate.

For this report a state of the art computer with 12 GB of working memory is used. Yet, the computer has not enough working memory to build the result grid because of the time dimension of 8760 hours. The maximal area the computer could process with the written python code in one run is 100 km², which took about 2 hours. A solution was found to eliminate the time dimension, but the implementation would have taken too long. Therefore approach b) is used instead. However, the python script is used in future research work.

The last methodological decision which is discussed here, is the placing criteria of the wind turbines. The two available options are:

a) According to the full load running hours, determined by the wind profiles and the two wind power curves

b) According to the long term average wind speeds and a limit wind speed for the respective turbine

Option a) takes into consideration how well the wind profiles fit to the wind power curve. Unfortunately the wind profiles are just available for one year and not as an average profile for a longer timeframe. The one year profile is not a sufficient long term indicator, based on which a wind turbine would be placed. Simply averaging different hourly annual profiles would smoothen the distribution of the wind speeds.

A solution to this problem is to extract the Weibull[29] parameters of the wind profiles and then distribute the long term annual average wind speeds according to the extracted Weibull parameters. That would ensure the site specific profile, but calibrated with the long term wind speeds. This approach could not be conducted, since the extraction of the Weibull parameters is complex and it was not possible to handle within the timeframe of this study. An example of such a calibration is given in (Lütkehus et al. 2013) on page 13 and conducted by ForWind[30]. In this study approach b) is used as a placement criteria for the wind turbines.

[29] http://www.weibull.de/WeibullHTML.htm
[30] http://www.forwind.de

7 Bibliography

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8 Appendix

8.1 The Simplify Tool in ArcGIS

The simplify tool in AcrGIS reduces the complexity of a feature either by erasing points of by bending the line. For larger datasets the point erase option is recommended to achieve a good computing performance. However in case of the street layer it is found, that the point erase option decreases the total area by about 30 per cent, which results in great inaccuracy. **Figure 23** gives a visual comparison of the two tool options. As it can be seen, the red polygons often join up in one point and therefore reduce the area. Other simplified layers have not been affected by this problem. It is expected that similar, rather straight shaped polygons, for example rivers, would be affected by this problem as well.

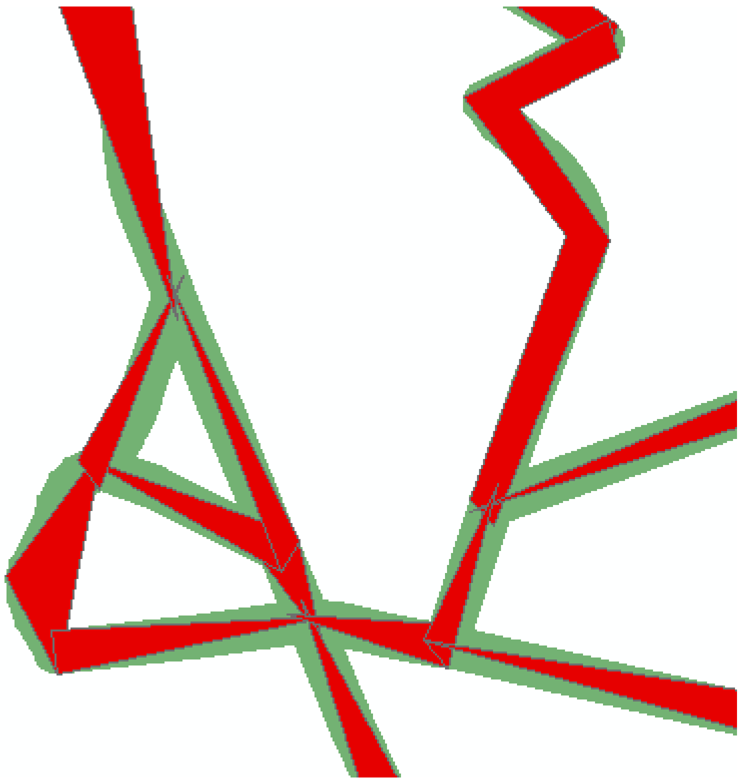

Figure 23: Simplify polygon options point erase (red) and line bend (green).

8.2 CD-ROM

On the attached CR-ROM to this report the following items can be found:

- The two placement models. Where the file "Scenario1and2.xlsx" is for the original model with two different wind turbines and the file "AlternativeScenario1and2a.xlsx" is for the scenarios where just one turbine is used. Be aware that both files slow down the computer and take a while to open. For performance reasons, no active formulas are saved in the cells. The used formulas are written as plain text above the cells. Further automatic recalculation is deactivated.

- The external input data for both placement models:

    - Total load curve: "130906_load_vload_D_2011.xlsx"

    - The 70 wind profiles: "Station_Windprofile.xlsx"

    - The average roughness lengths of each category in each sector, divided in five files: "CLC_DE_RoughnessLenghts_m_meanzonal_Wind_annual_avg_140m_extr_int_CLC_DE_RoughnessLenghts_m_meanzonal_Wind_annual_avg_140m_extr_int_XY_XY.xlsx"

The file geodatabase and the ArcGIS project files can be provided upon request, but are not attached to this report due to their size of about 8 GB.