Windenergy and repowering potential in Rhineland-Palatinate from 2021 until 2030

Master's Thesis submitted

to

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Contents

Abstract

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

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

List of Abbreviations

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

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1 Introduction

This work was executed and written in scientific recognition of the importance of reducing greenhouse gas emissions and expanding renewable energies to mitigate the effects of climate change. This study was also carried out on behalf of the state-owned energy agency [1] within the project "municipal greenhouse gas accounting and regional climate protection portals in Rhineland-Palatinate" [2] which is funded by the "European Regional Development Fund" [3] and the state of Rhineland-Palatinate. This project supports the creation of municipal climate protection measures in order to achieve the climate protection goals of the municipalities and the state and thereby increases regional added value, ensures sustainability and thus improves the quality of life of all citizens. When developing municipal climate protection, a sound strategy is required regarding the legally anchored striving for climate neutrality of the state of Rhineland-Palatinate (Landesklimaschutzgesetz §4, 2014, [4]). Even more pressure comes from the recent press release No. 31/2021 of April 29 in 2021 [5], in which the first Senate of the Federal Constitutional Court decided that the regulations of the Climate Protection Act of December 12 in 2019 [KSG, 2019] on the national climate protection targets and the annual emission quantities permitted up to 2030 are incompatible with fundamental rights, as there are no sufficient criteria for further emission reductions from 2031 onwards. It is stated that the legal requirements are not sufficient to bring about a timely transition to climate neutrality. The legislature has therefore published an adjusted edition of this act that strives for a faster development of renewable energies and the energy transition in general [6]. This shows that this study is also highly embedded in a socio-economic context. The energy transition is a cornerstone of a decent strategy to climate neutrality and Rhineland-Palatinate wants to play a pioneering role in the implementation of the energy transition. The state government publishes on its website that Rhineland-Palatinate will cover 100 % of its electricity needs from renewable energies by 2030. In addition to energy from the sun, water and biomass, two thirds of the electricity generated in 2030 should come from wind power and is therefore the subject of this master thesis [7]. The gross electricity generation in Rhineland-Palatinate from wind power rose in 2017 with 5.9 TWh to 29 % of the total 20.7 TWh generated electricity. The total consumption in the same year was 29.1 TWh [8]. It can be assumed that, on the one hand, electricity consumption will increase in the future due to the electrification of transport and domestic heating, and on the other hand, efficiency measures can also lead to a lower energy consumption. Various scenarios about future electricity consumption assume a slightly reduced to increased, but on average relatively unchanged electricity consumption for the whole of Germany in 2030 [9]. In order to achieve the self-set goals of using two thirds of the electricity demand from wind power with constant or higher electricity demand, electricity generation with wind turbines (WT's) must be increased to at least 14 TWh per year. If Rhineland-Palatinate wants to become independent of electricity imports, an increase to around 20 TWh is necessary. There are two ways of increasing the amount of electricity generated by wind energy. On the one hand, areas that are still available can be identified and built on with new WPP's. On the other hand, existing old systems, whose absolute electricity feed-in quantity is low, can be replaced by new, higher and more efficient systems through the so-called "repowering." The aim of this work is to develop a methodology for calculating the wind energy potential and its related area consumption at the state level as well as for the districts and association communities in Rhineland-Palatinate. With this results an evaluation of the desired expansion targets should be assessed. The central three questions of this work are therefore:

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

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

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

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

2 State of the art

2.1 Technical and physical basics

Wind energy has been used by humans for thousands of years, but the generation of electrical power has only been possible since the 19th century with the beginning of industrialization and is now the subject of constant research and development in the context of the energy transition [10]. A wind turbine usually consists of the three main components rotor blades, nacelle and tower. The nacelle contains besides other elements the gearbox, the generator, the transformer and the control system

[11]. The mostly three rotor blades are attached to the rotor hub and absorb the kinetic energy of the wind and convert it into a rotary motion. If the winds are too strong, the rotor blades can be “taken out of the wind” by adjusting the blades, thus protecting the system from damage. Mainly the gearbox and the generator convert the kinetic energy into electricity. However, there are also systems with direct drive and without gear. The nacelle can be rotated to an optimal position when the wind conditions change, and an electromagnetic brake helps to shut down the system when the winds are too strong or during maintenance work. In addition to its load-bearing function, the tower also contains the power lines that conduct electricity to the grid connection of the distribution network [12].

The transmission system operators, in this case Amprion, are obliged to publish master and so-called movement data for each calendar year in accordance with section 77 Renewable Energy Act 2017. These movement data include the annual electricity generation and the underlying tariff for each renewable energy system. The movement data for Rhineland-Palatinate are currently available until 2019. The total amount of electricity fed in with remuneration in 2019 from wind turbines in RLP is 6,782,180,753 kWh, i.e. approx. 6,782 TWh [13].

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

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

The air throughput or mass flow $\hat{m}$ that flows through the area swept by the rotor blades in a certain time can be calculated by multiplying the air density, rotor area and wind speed as well as the time interval required with[2]:

$$\hat{m} = \rho AV \tag{2}$$

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

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

(Mac Kay [ref] and BWE [ref])

Of course, not all the wind’s power can be converted and there are further losses when converting kinetic energy into electrical energy in the generator. The efficiency in theory is a maximum of 59%

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

and in practice it is often around 40 % to a maximum of 50 % [reference]. In Formula 3, however, it becomes clear that the wind speed is the decisive factor for the performance of the wind and thus a wind turbine. If the wind speed increases three times, the power is 27 times greater. It can also be seen that the amount of energy increases proportionally with increasing rotor diameter. This explains why the rotor diameters become larger in practice. Due to the higher and more constant wind speed with increasing height, the hub heights also increase. The development of the rotor diameter and hub heights are shown in figures 1 and 2. For the classification of the technical development and the calculation method, the study of the German Wind Guard (DWG) “Full load hours of wind turbines on land - development, influences, effects” from October 5th, 2020 [reference], is used as a guide and its results are presented. The study examines the development of the full load hours and thus also the wind energy potential in Germany and is divided into the sub-areas Schleswig-Holstein (SH), north (Norden), centre (Mitte) and south (Süden). Rhineland-Palatinate is part of the southern region. The

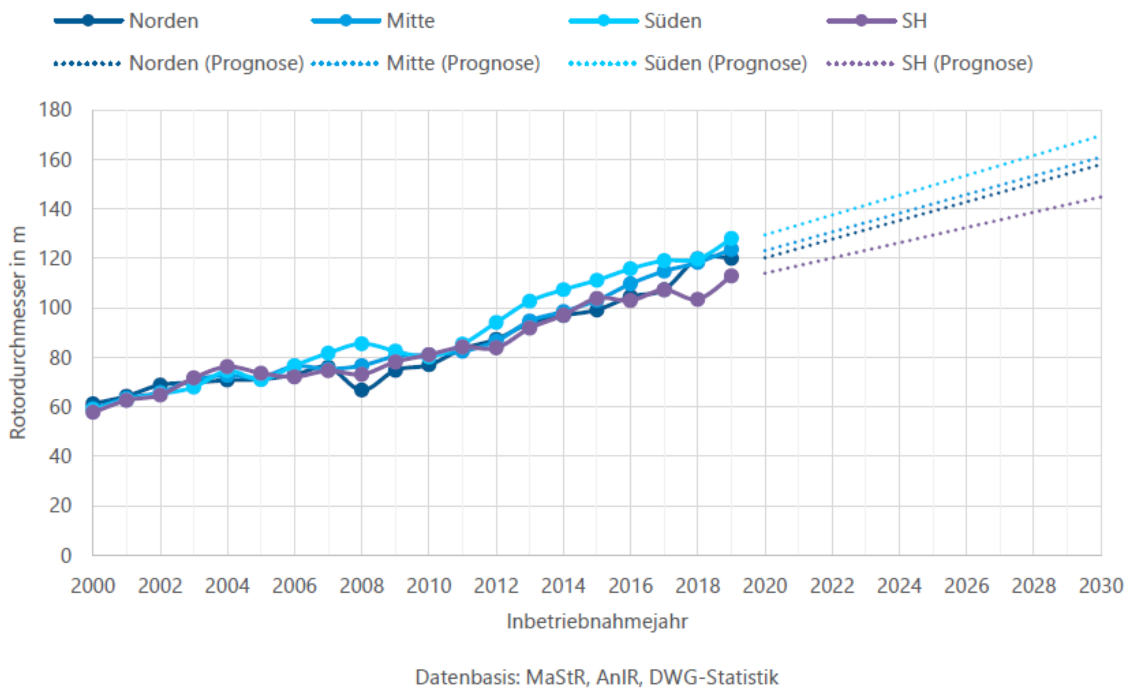

Figure 1: Development and forecast of the mean rotor diameter according to Deutsche WindGuard, 2020

study of DWG suggests that the wind energy potential, i.e. the theoretical electricity yield of a wind turbine for future systems, can and will be calculated in this work using the following formula:

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

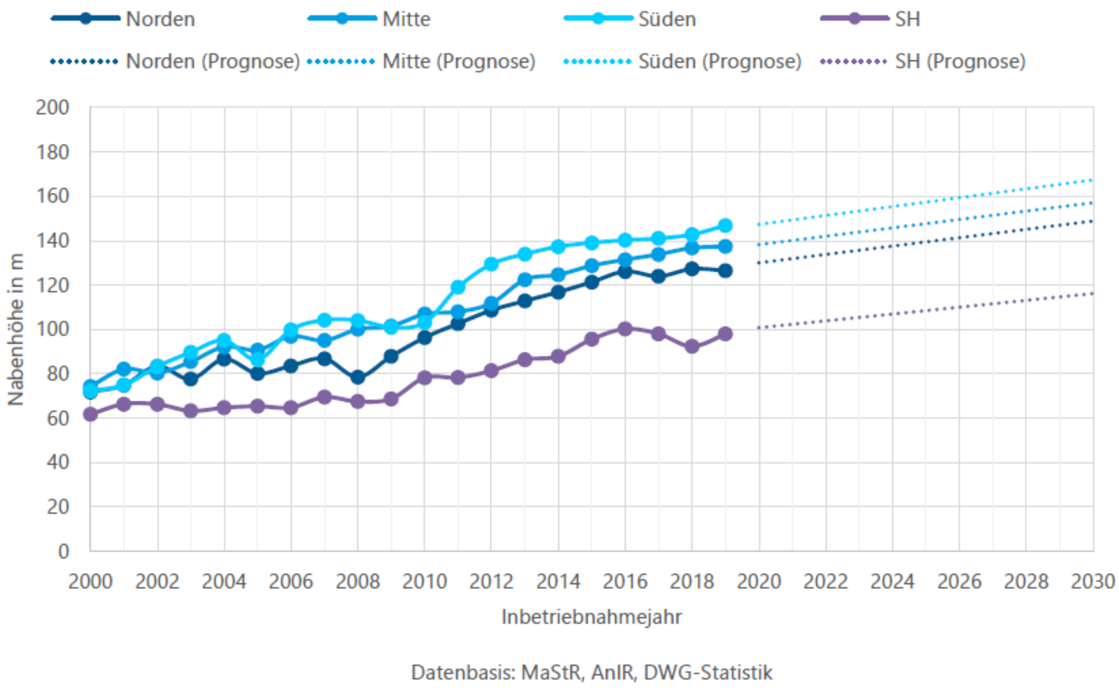

Figure 2: Development and forecast of mean hub hight according to Deutsche WindGuard, 2020

The capacity is the installed nominal output, also called **rated capacity** of the generator and can be found in the technical details of a wind turbine generator. The development of the installed nominal power depending on the commissioning date in Germany can be seen in figure 3. The **full load hours** are formed from the quotient of the annual electricity yield and the rated capacity and are an indicator of the degree of utilization of a wind turbine. The full load hours number the hours that the system would have to be operated under nominal load in order to deliver the amount of electricity generated and do not reflect the actual operating time below nominal load. Since the full load hours result from the electricity yield and the installed nominal power, there is a dependency and the gain in information is limited. However, the full load hours are a useful concept in order to be able to draw conclusions about the electricity yield and, therefore, analysis of the full load hours of Rhineland-Palatinate are presented in Section 3.2.3. The development of full load hours in Germany can be seen in figure 4. If two plants have the same hub height and the same rotor diameter, but a different nominal power, the less powerful plant, i.e. the plant with the lower **specific nominal power**, will achieve more full-load hours but a lower annual energy yield at the same wind speeds. The full load hourly value should therefore always be considered and evaluated in connection with the energy yield.The specific nominal power represents the relationship between the nominal power of the turbine and the swept rotor area. The specific nominal power of the turbines has tended to decrease since 2012, which is due to the increasing rotor diameters figure 1. Systems with a lower specific nominal output, i.e. comparatively larger rotors,

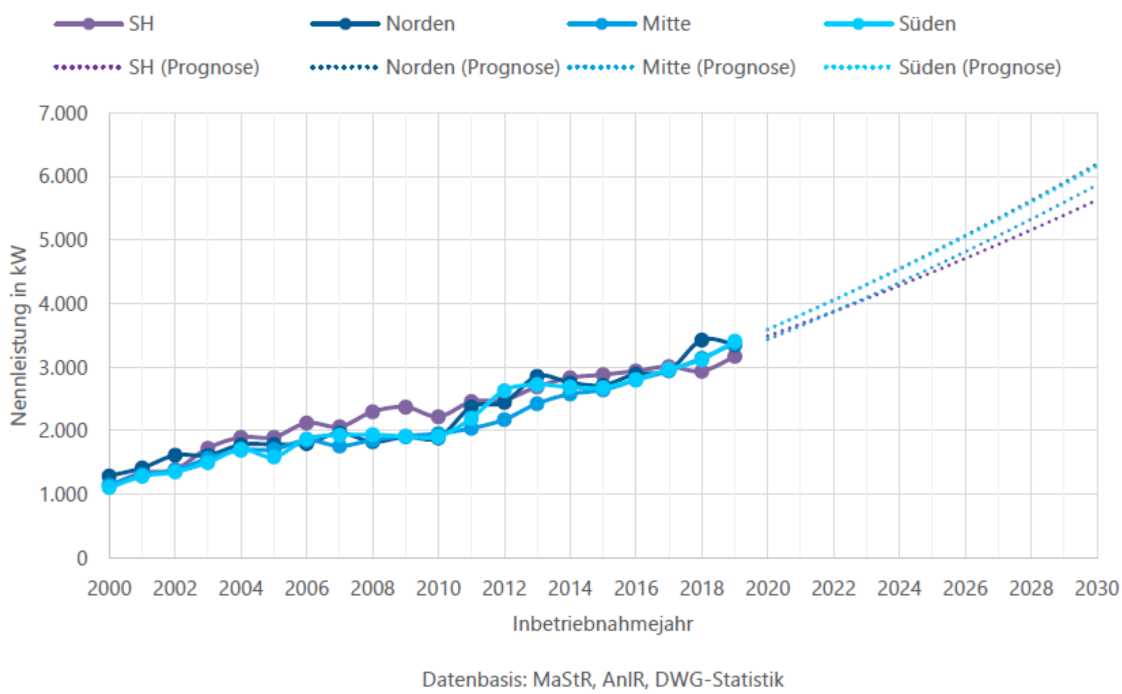

Figure 3: Development and forecast of the mean rated capacity according to Deutsche WindGuard, 2020

have more full-load hours under the same wind conditions or achieve their nominal output at lower wind speeds and are therefore also referred to as low-wind systems. If you compare two systems with the same rotor diameter, the system with a higher absolute and therefore also specific nominal output is always more expensive and is therefore only suitable for comparatively higher wind speeds. Due to the prevailing conditions in Rhineland-Palatinate, low-wind turbines with a lower specific nominal output are more important in repowering than the increase in absolute turbine output. However, the value of the specific rated capacity in southern Germany is currently stagnating at approx. 270 W / m² seen in figure 5. Because the full load hours depend largely on the rated capacity and the wind speed in addition to technical influences, they are a useful indicator for calculating the expected electricity yield if there is no data on electricity yields from existing systems, only technical details and site conditions are available. The mean value of the full load hours of all wind turbines, e.g. of a federal state, can be used as a parameter to infer the future electricity yield from the installed rated capacity.

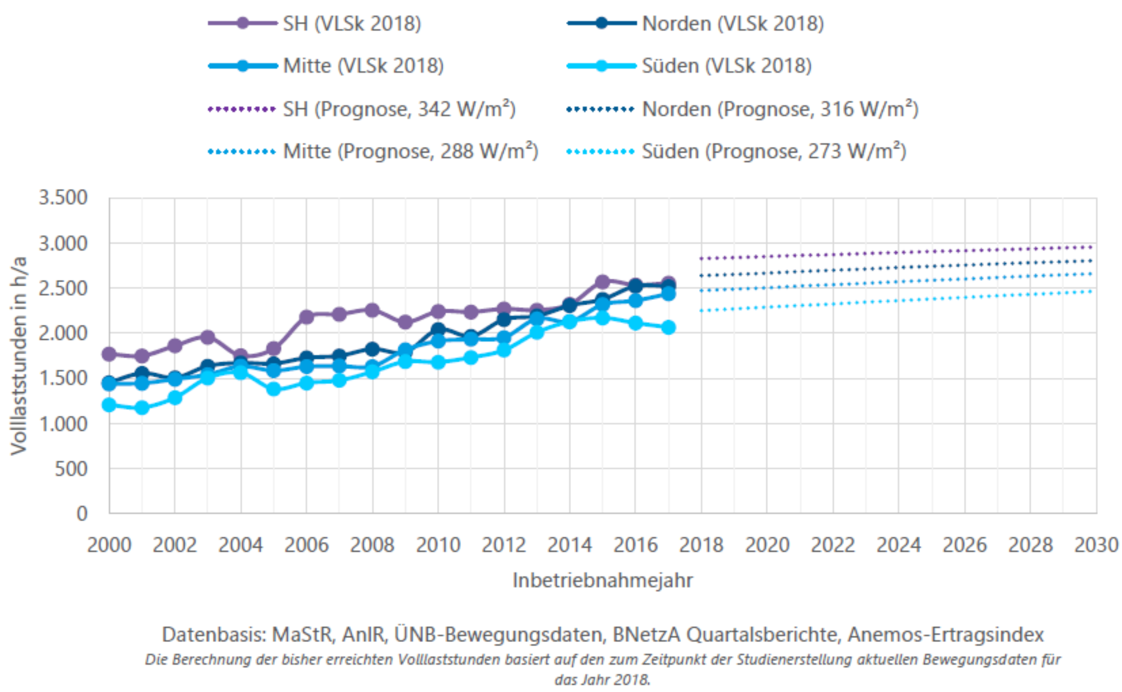

Figure 4: Development and forecast of the mean full load hours according to Deutsche WindGuard, 2020

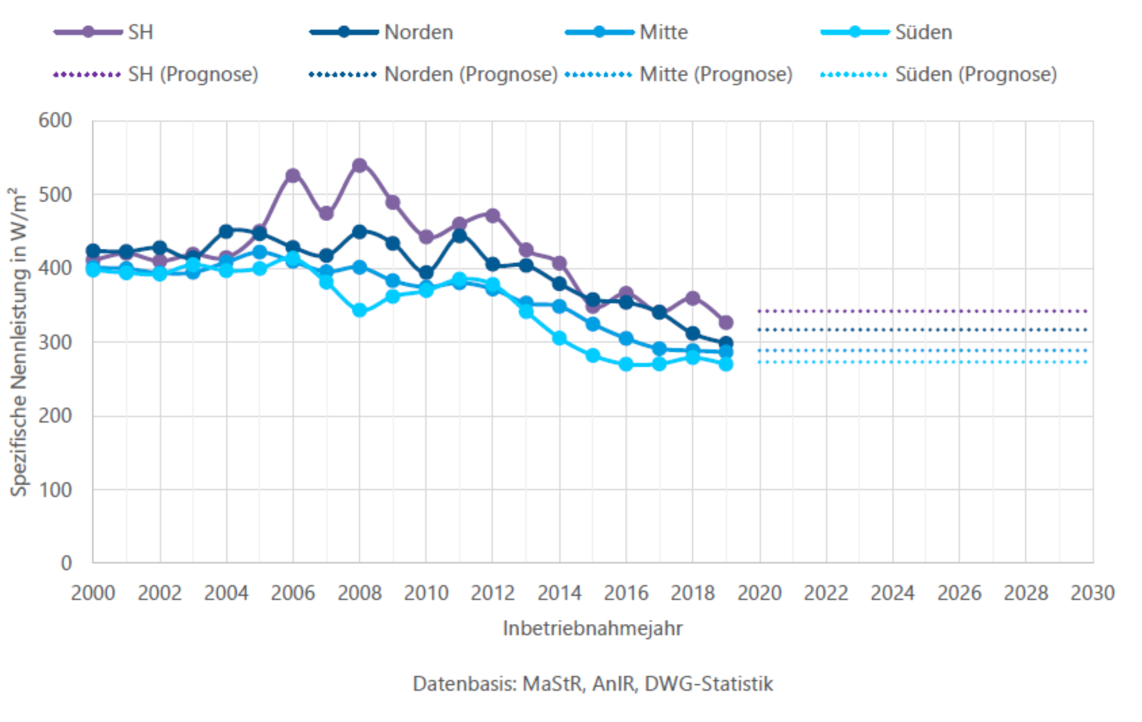

Figure 5: Development and forecast of the mean specific rated capacity according to Deutsche Wind-Guard, 2020

2.2 Résumé and trends of development

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

3 Data

- Describe the data and its quality.
- How was the data sample selected?
- Provide descriptive statistics such as:
  - time period,
  - item number of observations, data frequency,
  - item mean, median,
  - item min, max, standard deviation,
  - item skewness, kurtosis, Jarque–Bera statistic,
  - item time series plots, histogram.
- For example:

	3m	6m	1yr	2yr	3yr	5yr	7yr	10yr	12yr	15yr
Mean	3.138	3.191	3.307	3.544	3.756	4.093	4.354	4.621	4.741	4.878
StD	0.915	0.919	0.935	0.910	0.876	0.825	0.803	0.776	0.768	0.762

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

- Allows the reader to judge whether the sample is biased or to evaluate possible impacts of outliers, for example.
- Here tables can be easily integrated using the `kable()` function in the `knitr` package (with perhaps some additional help from the `kableExtra` package). `kable()` will automatically generate a label for the table environment. That way you don't have to manually enter in the table in LaTex, you can embed tables from R code.
- Tables can be referenced using `\@ref(label)`, where `label` is `tab:<name>`, where `<name>` is the code chunk label.
- The appearance may look different to tables directly typed with LaTex, due to limitations in `kable()`. To compare:

	3m	6m	1yr	2yr	3yr	5yr	7yr	10yr	12yr	15yr
Mean	3.138	3.191	3.307	3.544	3.756	4.093	4.354	4.621	4.741	4.878
StD	0.915	0.919	0.935	0.910	0.876	0.825	0.803	0.776	0.768	0.762

Table 2: This table was handwritten with LaTeX.

4 Results

5 Conclusion

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

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A Appendix

Here goes the appendix!

A.1 Figures

A.2 Tables

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

Table 3: Detailed descriptive statistics of location and dispersion for 2100 observed swap rates for the period from February 15, 1999 to March 2, 2007. Swap rates measured as 3.12 (instead of 0.0312).

Declaration of Authorship

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

Berlin, July 01, 2021

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Elias Cuadra Braatz