Potential in Systematically Placing a High Capacity of PV and Wind Sources in Germany

Storage and Transmission Capacity Requirements Analysis and a Case Study on Morocco

BY

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DISCLAIMER

To the best of my knowledge I do hereby declare that this thesis is my own work. It has not been submitted in any form of another degree or diploma to any other university or other institution of education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Kassel,

28.02.2012,

Arabi Abdelhaq
Executive Summary

The world is facing new challenges related to depleting natural resources, expanding economies, and an ever-growing population with resource-intensive life styles. Accordingly, policymakers must actively analyze different combinations of available renewable energy technologies as viable solutions to these challenges. The ultimate objective is to provide diverse options for the effective utilization of renewable energy both in the present and the near future.

This MATLAB-based technical study analyzes the potential of a systematic-optimized placement of wind turbines and Photovoltaic panels (PV) to minimize the requirements for the energy supply structure by reducing the residual load in Germany. A simpler case study is also presented for Morocco.

This study seeks to analyze the installed capacity required to ensure that PV panels and wind turbines contribute to reduce significantly the residual load in Germany based on the allocation methods used in this study. In addition, Germany was divided into six regions to see the impacts of optimizing the installation of PV and wind capacity in small regions to the whole system, allowing us to take into consideration transport and storage capacity requirements needed to consistently fulfill the maximum load demand.

The “six regions” scenario proposed in this study, with a total installed capacity of 238.01 GW reduces the average residual load by 69.18%. This is an improved figure from the 65% residual load reduction by the other Germany as one region scenario. Moreover, load flow with a mean value of 1,474 MW for the lines transmission capacity is established through a Direct Current (DC) grid between the regions to balance all the hourly lack and excess of power before using storage of a 17 GW range and a capacity of 141.737 TWh to completely make up for the hourly differences between load demand and generation.

These results for storage capacity requirements and transport were compared to two scenarios: Germany as one region scenario and another reference scenario, and results showed that maximum transport capacity needed is 27% and 12% less than the two scenarios respectively and capacity storage requirements are 13% and 2% less respectively. This demonstrated the usefulness of using the smaller regions model as an optimization approach to reduce storage and transmission requirements taking into account the whole supply structure.

The case study on Morocco provides a theoretical estimation of the installed PV and wind capacity required to fully cover the yearly energy consumption and was found to be 19,520 MW and 12,250 MW for PV and wind respectively. Storage requirements are studied for each case and show a clear differentiation between the characteristics of this storage for each source were PV accumulated storage requirements are 27% less than wind.
Acknowledgments

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Abbreviations and Acronyms

CC: Correlation Coefficient
DC: Direct Current
DCFLM: Direct Current Flow Load Matrix
DCTP: Duration Curves of the Transmission Performance
GHI: Global Horizontal Irradiance
LF: Load Flow
MENA: Middle East and North Africa
PTDF: Power Transfer Distribution Factor
PV: Photovoltaic
RES: Renewable Energy Sources
RL: Residual Load
RLDC: Residual Load Duration Curves
TP: Transmission Performance
1. Introduction

1.1. Motivation of the work

Germany aims to source 80% of its electrical demand from renewable sources by 2050\(^1\) and studies show that a 100% renewable energy share is even possible by then\(^2\). Accordingly, analyzing the transformation of Germany’s energy supply system by fluctuating renewable energy serves as a valuable model of shifting towards a highly renewable energy scenario.

In order to reach a high renewable energy share of the total energy generation in Germany, one needs to consider the energy consumption, study the available resources, and employ sound methodologies required for putting renewable energy plants in place.

The primary challenge in this analysis is to match Germany’s energy demand to PV-wind energy generation to accommodate supply excess and shortages. To overcome this problem, large storage and transmission capacity will be needed. We must keep in mind, that the allocation of PV and wind must not be based only on where the sources are available as it is not necessarily the economic optimum.

Therefore, sound allocation methods of these two sources must be studied to consider for other factors: the percentages of the unused excess energy, the contribution to load covering, and fitting the generation to the load and reducing the load peaks.

In Morocco, with its low electrical demand, and its high solar radiation and wind resources, the focus was to get an idea of its export capacity and storage requirements from each resource in a 100% renewable scenario.

1.2. Problem Statement and Research Objectives

The research objectives are to make qualitative predictions that answer these questions:

- Could we improve meeting the load demand by specific site selection?
- Could we significantly reduce waste due to excess energy generation by specific site selection and equalize yield losses caused by the selection?
- Could we reduce the demand for transmission and storage capacity?
- What effects on these qualitative predictions could we get if we move from a Germany as one region scenario to a regional scenario to make an “optimized” site selection?

\(^1\) Press release No. 012/11 by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
\(^2\) Study by Fraunhofer Institute: 100% renewable electricity supply by 2050
1. Introduction

By answering these questions, decision-makers in Germany and Morocco shall be able to decide on new incentives for future allocation of major wind-PV farms, and should be able to develop indicators to raise awareness about the limitations and possibilities to reach the 100% renewable energy using PV and wind. In addition, policy makers should have an indication about the required infrastructure for the new Direct Current (DC) network to cover the load based on the results of this study.

It is important to note, that this study is a first approach for an improved site selection, only three factors for optimization are considered which will be discussed in detail, and there should be far more to get a better simulation quality. Therefore, the results are only qualitative hints to the effect of a specific site selection.

1.3. Hypothesis

It is possible that wind and PV sources can address a large part of the energy consumption needs in Germany and reduce the residual load by following specific - well managed - energy allocation methods that take into consideration the load demand profile and its matching with the available PV-wind share. Furthermore, it is possible to optimize this matching and reduction in residual load by analyzing on a micro-level, different regions within Germany and including transfer and storage possibilities.

Figure 1 shows Germany divided into the small pixels used in this study to simulate different results.

---

3 A definition of the “pixel” will follow in chapter 4
2. A Brief Literature Review

Several studies have researched a 100% renewable mix between various renewable energy resources. The main difference between these studies has been the geographical location of the study, and the type of renewable sources chosen to investigate while applying different research methodologies.

*In the study of Joakim Widén*[^1] on the correlations between large-scale solar and wind power in a future scenario for Sweden, the author studied the correlation between wind and PV farms in different parts of the country.

The smoothing effect was thus analyzed by using the sample correlation between wind and solar power as an allocation strategy for wind and PV farms.

The time variability and coincidence in certain locations proved that there is a negative correlation between solar and wind outputs and that using large-time scales provides for the strongest correlation.

*Another study by Dominik Heide, Lueder von Bremen, Martin Greiner, Clemens Hoffmann, Markus Speckmann, and Stefan Bofinger*[^2] presented results similar to the research presented in this study, although it focuses on the EU. The results drawn highlight the optimal mix between PV and wind in a highly renewable scenario standing at 55% wind, 45% PV shares and examine the effect on the storage size in such a mixed share scenario as opposed to a wind-only or PV-only scenario.

*A study by Thomas Nikolakakis and Vasilis Fthenakis*[^3] focused on New York State, and examined the New York state grid and the maximum penetration possibilities by different RES, taking into consideration different scenarios and mix shares.

*In his study conducted in Spain, Ghassan Zubi*[^4] concluded that at least 80% PV and Wind share proved to be the basis for any economical highly renewable futuristic scenario, and a technical mix of 30% Wind and 15% PV.
3. Technical Background

3.1. Historical Background on the available PV and Wind energy sources situation in Germany and their complementarities

Germany has a leading role in the development and employment of PV and wind renewable energy sources. It topped the rankings of countries based on the total installed wind capacity by the end of 2011 with 28.576 GW installed wind capacity, meeting around 6.3% of its load demand in addition to 24.8 GW of installed PV capacity by the end of 2011.

In 2010, Germany added more PV capacity than all the world capacity installed in 2009. With the additional investment in renewable energy, Germany ranked first for PV and fifth for wind technology capacity added annually. As for its existing capacity, Germany ranked first for PV and third for wind.

Germany met 11% of its final energy consumption with renewable resources in 2010. Wind power accounted for nearly 36% of renewable generation, followed by biomass, hydropower, and solar photovoltaic (PV).

In Germany, as anywhere else, the issue of complementarities between PV and wind power generation is important; the better correlated PV and wind generation are with the load, the more beneficial it will be for the grid to accommodate this share. Moreover, the generation of energy based on these resources is directly dependent on weather conditions. On the other hand, the spatial distribution of these resources has an effect on the correlation with the load.

PV and wind resources are intermittent resources; there is no PV generation at night, and its generation increases and decreases daily, depending on weather conditions, cloud formation, and shading, among other factors. Alternatively, wind generation is less predictable within a certain time period compared to PV and has sharper generation curves than PV due to its high temporal dependency.

A higher correlation between wind and PV with load demand reduces storage requirements of the generated energy. Therefore, this study focuses on the effect of correlating PV and wind sources with the load.

\[\text{footnotesize}{\text{4 The figures in the second and third paragraphs are taken from the reference mentioned at the end of paragraph 3}}\]

\[\text{footnotesize}{\text{5 Source: http://windmonitor.iwes.fraunhofer.de/}}\]

\[\text{footnotesize}{\text{6 This percentage is extrapolated from 6\% load met found in reference 5 for the year 2010.}}\]

\[\text{footnotesize}{\text{7 Press Release: Zubau an Photovoltaik-Anlagen 2011 noch h\öher als im Rekordjahr 2010 -}}\]

\[\text{footnotesize}{\text{http://www.bundesnetzagentur.de. 7.5 GW from this reference were added to the figure from reference 5 to make 2011 figure.}}\]
3. Technical Background

3.2. PV and Wind Energy Allocation Methods

Three methods are applied to determine the allocation of wind turbines and PV modules: The correlation coefficient method, covering the residual load method, and covering the residual load peaks method.

A ‘suitability factor’, described later in the section, is the formula that connects and weighs the contribution of these three methods for the allocation of different PV and Wind capacity.

3.2.1. The Correlation Coefficient

The correlation coefficient (ρ) between two data sets quantifies the relationship between these \(^{[6]}\), and can be seen mathematically from the following formulas, as the covariance of the two data sets we have, divided by the product of their standard deviations.

In this study, the two data sets are the PV power generation time-series, \((pv)\), against the load demand time-series, and second, between the wind power generation time-series \((w)\) against the same load demand time-series.

Equations 1 and 2 are the mathematical forms of the correlation coefficient, where the numerator describes the covariance of the data, Equations 3 and 4, and the denominator describes the variance of the two data sets, namely PV against load demand and wind against load demand.

\[
\rho(pv,l) = \frac{C(pv,l)}{\sqrt{C(pv,pv)C(l,l)}} \tag{1}
\]

\[
\rho(w,l) = \frac{C(w,l)}{\sqrt{C(w,w)C(l,l)}} \tag{2}
\]

Where,

\[
C(pv,l) = \sum_{t=1}^{T=8760} (pv_t - \mu_{pv})(l_t - \mu_l) \tag{3}
\]
3. Technical Background

\[ C(w, l) = \sum_{t=1}^{T=8760} (w_t - \mu_w)(l_t - \mu_l) \]

In Equations 5, 6 and 7, \( \mu_{pv} \), \( \mu_w \) and \( \mu_l \) are the mean values of the PV, wind, and load demand data sets respectively.

\[ \mu_{pv} = \frac{1}{T} \sum_{t=1}^{T=8760} (pv_t) \]

\[ \mu_w = \frac{1}{T} \sum_{t=1}^{T=8760} (w_t) \]

\[ \mu_l = \frac{1}{T} \sum_{t=1}^{T=8760} (l_t) \]

This method is used to indicate us how well the wind or PV power generation time-series correlate (or are in harmony) with the load demand time-series and is measured with a value ranging from of 1 to -1, whereby 1 means that the variables are totally correlated and -1 means that variables are negatively correlated between these two sets. Equation 8 states:

\[ -1 \leq \rho \leq +1 \]

3.2.2. Covering the Residual Load

The residual load is the load demand that has not been covered by the PV and wind sources. We include this method to cover the load by the generated PV or wind found in the chosen pixel that covers the largest share of this load in comparison with other pixels.

Equation 9 describes the solar energy fraction added to reduce the residual load each time the method is employed after each loop\(^8\). Of course, this applies to the wind fraction added when wind is favored for installation at a certain step.

\[ DA_{PV} = \sum \text{normalizedPV time-series} \times \text{energy added} \]

\( DA_{PV} \) refers to the solar fraction added, in [MW], and the normalized PV power generation time-series is the normalized PV power generation time-series [per unit], and the energy added

\(^8\) A description of the simulation model used is discussed in the following chapter
or the *step size* is a pre-defined value for the available PV or wind potential, which allows the installed capacity to increase by a certain value [MW].

Where for each hour we check if the normalized PV power is bigger than the load. If this power is bigger than the load then DA_PV would equal the load, and if not, the DA_PV equals the normalized PV power.

This procedure applies on the different locations or regions in the country, these pixels which fall just under the residual load curve are considered for further processing whilst these areas that fall above the residual load curve (apparently exceeding it) would not be assigned for further processing in this method, but would however, be considered in the third method, namely, covering the residual load peaks.

### 3.2.3. Covering the Residual Load Peaks

The goal of this method is to cover the load profile peaks by installing PV and wind capacity in locations where they best cover the load peak to limit or reduce the needed backup capacity.

We first establish the limit which defines a residual load peak, which in this investigation, is less than 10% of the residual load demand peak, Figure 2. After that, hours are determined for which this residual load peaks occur, and values of each residual load peak are recorded.

Finally, the best load peaks covering PV or wind normalized power time-series are used to cover this residual load peak by a certain step size as discussed earlier.

![Figure 2: Residual load for Germany with 10% over Maximum Residual Load Limit](image)
3.2.4. The Suitability Factor

Equations 10 and 11 describe the PV and wind sources’ ‘suitability factor’, which is the selection criteria defined as the multiplication of the three methods outputs raised to a suitable power$^9$.

At first all the three factors are normalized by the respective maximum to adjust their influence in respect to the suitability factor, while the +1 value number added to the CC_PV 1 is added before it is normalized, so that we get only positive values.

The suitability factor is used to weigh the contribution of the three upper mentioned methods, and in so doing, decides whether a PV or wind capacity shall be installed, based on a higher ‘suitability factor’ value between both.

\[ \text{Suitability factor}_{PV} = \left( \frac{\text{CC}_{-PV} + 1}{\text{MaxCC}_{-Pv}} \right)^{\text{PowerCC}_{-PV}} \times \left( \frac{\text{DA}_{-PV}}{\text{MaxDA}} \right)^{\text{PowerDA}_{-PV}} \times \left( \frac{\text{DA}_{-LS - PV}}{\text{MaxDA}_{-LS}} \right)^{\text{PowerDA}_{-LS}} \]

\[ \text{Suitability factor}_{W} = \left( \frac{\text{CC}_{-W} + 1}{\text{MaxCC}_{-W}} \right)^{\text{PowerCC}_{-W}} \times \left( \frac{\text{DA}_{-W}}{\text{MaxDA}_{-W}} \right)^{\text{PowerDA}_{-W}} \times \left( \frac{\text{DA}_{-LS - W}}{\text{MaxDA}_{-LS - W}} \right)^{\text{PowerDA}_{-LS - W}} \]

$^9$ The power values were chosen arbitrarily for each term. However, they are representative of the significance of each method to the suitability factor value, and moreover, they could be altered based on a more scientific reasoning.
Table 1 describes the 18 terms used in the suitability factor equations for PV and Wind.

<table>
<thead>
<tr>
<th>Terms used in Equations 10 and 11</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC_PV</td>
<td>Correlation coefficient matrix for all pixels and classes of tilt and orientation angles</td>
</tr>
<tr>
<td>MaxCC_PV</td>
<td>Overall maximum correlation coefficient of PV’s correlation coefficient matrix</td>
</tr>
<tr>
<td>PowerCC_PV</td>
<td>Power of the first term for PV suitability factor</td>
</tr>
<tr>
<td>DA_PV</td>
<td>Residual load cover matrix for all pixels and classes of tilt and orientation angles</td>
</tr>
<tr>
<td>MaxDA</td>
<td>Overall maximum residual load cover percentage of PV’s residual load cover matrix</td>
</tr>
<tr>
<td>PowerDA</td>
<td>Power of the second term for PV suitability factor</td>
</tr>
<tr>
<td>DA_LS_PV</td>
<td>Peak residual load cover matrix for all pixels and classes of tilt and orientation angles</td>
</tr>
<tr>
<td>MaxDA_LS</td>
<td>Over all maximum cover percentage of the residual load peaks</td>
</tr>
<tr>
<td>PowerDA_LS</td>
<td>Power of the third term for PV suitability factor</td>
</tr>
<tr>
<td>CC_W</td>
<td>Correlation Coefficient matrix for all pixels and chosen hub heights</td>
</tr>
<tr>
<td>MaxCC_W</td>
<td>Overall maximum correlation coefficient of Wind’s correlation coefficient matrix</td>
</tr>
<tr>
<td>PowerCC_W</td>
<td>Power of the first term for Wind suitability factor</td>
</tr>
<tr>
<td>DA_W</td>
<td>Residual load cover matrix for all pixels and chosen hub heights</td>
</tr>
<tr>
<td>MaxDA_W</td>
<td>Over all maximum residual load cover percentage of Wind’s residual load cover matrix</td>
</tr>
<tr>
<td>PowerDA_W</td>
<td>Power of the second term for Wind suitability factor</td>
</tr>
<tr>
<td>DA_LS_Wind</td>
<td>Peak residual load cover matrix for all pixels and chosen hub heights</td>
</tr>
<tr>
<td>MaxDA_LS_W</td>
<td>Over all maximum peak residual load cover percentage of Wind’s peak residual load cover matrix</td>
</tr>
<tr>
<td>PowerDA_LS_W</td>
<td>Power of the third term for Wind suitability factor</td>
</tr>
</tbody>
</table>

Table 1: Terms Used in the Suitability Factor Calculation for PV and Wind
4. The Model

The model on which the results and analysis are based, was developed with the Matlab program. A description of the data employed, the inputs and assumptions necessary for the model, the equations used, and the algorithm will be presented in this chapter.

4.1. Data Used

4.1.1. Input Data
Before presenting the input data used in the model, it is important to present the concept of a pixel, which we use when we refer to a point on the map of Germany. Each pixel therefore, is a coordinate that defines a geographical location. In Germany, 3027 pixels are numbered and used. Each pixel equates an area of approximately 140 km².

The following input data is provided in matrix form to the program and a range of different matrix sizes exists which are shown between brackets for each input:

- Coordinates of each pixel in Germany (longitude, latitude) [3027 x 1].
- Time-series of electrical load demand of Germany [8760 x 1].
- Potential of PV sources per pixel [3027 x 1].
- Wind potential per pixel [3027 x 1].
- Normalized time-series for PV generation [8760 x 3027 x 190].
- Normalized time-series for wind generation [8670 x 3027 x 1].
- The population of Germany per pixel [3027 x 1].

The input data was re-arranged into six regions of Germany, which will be later presented in the following section of this study.

<table>
<thead>
<tr>
<th>Region number</th>
<th>Number of pixels</th>
<th>Coordinates limits</th>
</tr>
</thead>
</table>
| 1             | 491              | Longitude (6.3125 to 10.4375)  
|               |                  | Latitude (47.3750 to 49.8750) |
| 2             | 679              | Longitude (5.9375 to 10.4375)  
|               |                  | Latitude (50.0000 to 52.3750)  |
| 3             | 409              | Longitude (6.6875 to 10.4375)  
|               |                  | Latitude (52.5000 to 55.0000)  |
| 4             | 406              | Longitude (10.5625 to 13.8125)  
|               |                  | Latitude (47.3750 to 49.8750)  |
| 5             | 582              | Longitude (10.5625 to 15.0625)  
|               |                  | Latitude (50.0000 to 53.1250)  |
| 6             | 460              | Longitude (10.5625 to 14.4375)  
|               |                  | Latitude (53.1250 to 54.6250)  |

Table 2: Academic Division of the Regions in Germany
4. The Model

4.1.2. Wind, Solar and Load Demand Data

The use of the most complete and up-to-date data available is vital to the accuracy of the simulation results. In this section, the compilation of wind, solar and load demand data used in the model is described in some detail.

4.1.2.1. Wind Data

The normalized (per unit) time-series generation curves were provided in one matrix of [8760 x 3027]; for 8760 hours and 3027 pixels for 2009. A sample of this normalized wind time-series generation curve combined with the PV generation at selected tilt and orientation angles is shown in Figure 3.

![Wind Power vs. PV Power - 12 months](image)

Figure 3: PV vs. Wind Generation in Pixel One
In this research, the technical potential of wind energy in Germany is used, the data showed all the locations (coordinate points) in the map of Germany which had a potential of 5 MW, and these data were later refitted to suit the 3027 points used in this model.

4.1.2.1.1. Wind Power Normalized Time Series Simulation \[^7\]

A physical model is the basis for the simulation of power from wind turbines, and calculations are based on stored performance characteristics and wind speeds time series.

Wind speeds are derived from the COSMO-EU model (which is a numerical weather prediction system for the German weather service), and have the same pixel spatial resolution of \([1/8^\circ \times 1/8^\circ]\), with a temporal resolution of one hour.

Taken that a neutral stratification is present, wind speeds are taken at hub height and a logarithmic wind profile is thus used. Other effects such as shading by other adjacent wind turbines are taken into account.

4.1.2.2. Solar Data \[^8\]

4.1.2.2.1. Technical PV Potential

PV system components and nominal capacity were evaluated and compiled, from different sites, and were matched with the zip code (address) from the sites were they were collected.

PV potential on roofs and facades was identified for residential and industrial zones based on the zip code of the site, and their calculation based on the Information coordination on the Environment project CORINE \[^9\] data (See Figure 4). Satellite images were used with a spatial resolution of \([100 \times 100 \text{ m}]\) where linear objects such as roads, rivers, railways, power lines and even small villages were not detected.

Moreover, certain deviations from reality are expected, such that potential for protected areas was calculated and included.

PV potentials along highways and railways were calculated using a model called the basic digital landscape model (Base DLM) describing the topographical features of the landscape.

The data was finally collected by the individual German states and represent the highest spatial resolution possible.
4. The Model

4.1.2.2.2. PV Power Normalized Time-series Simulation

Global radiation data were derived from satellite images for 2009 and were used to simulate the PV power normalized time-series, and power losses due to heating of the modules were taken into account.

The spatial resolution of the simulated data was the same for pixels, i.e. [14 x 10] km² with a time resolution of one hour.

The different configurations of tilt and orientation angles were taken into account, and a standard Polycrystalline module was used and justified because this PV module has a share of about 60% of the installed modules.

Moreover, considering different module types was not justified since the impact on performance was marginal.

Figure 5 shows the simulated technical potential data that was used for wind and PV in the model (compare the technical potential of PV in Figure 5 with Figure 4).
4. The Model

4.1.2.2.3. Load Demand Data

Load demand data of Germany was provided for the year 2009, and then, values of population per pixel were also provided and later used to scale the load demand data according to the region for which the simulation is run. The load demand curve is shown in Figure 6.
4.2. The Program Algorithm

As can be traced from the chart flow in Figures 7 and 8, the program starts with defining several assumptions and uses available sets of data that correspond to the specific objective sought to be achieved; therefore, these values are fixed throughout the run time of the program.

Other scenarios could be formulated based on different assumptions and the availability of data, rather than those presented in the following table, for example, changing the total capacity to install or using other normalized power curves for wind at different elevations.

Table 3 describes these assumptions and a range of corresponding values used in the simulation, the last column states if the value has been changed in the final results generation.

The values presented here are the ones used to run the simulation of Germany as a one region model that will be discussed in the following chapter. The same assumptions were also used for the simulation of Germany divided to regions, but certain values were changed depending on the region under study, for example, the capacity to install or load in the region…etc
4. The Model

<table>
<thead>
<tr>
<th>Assumption for</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity to install [MW]</td>
<td>Germany: 237 908</td>
</tr>
<tr>
<td></td>
<td>Regions: Table 7</td>
</tr>
<tr>
<td>Power for weighing energy allocation</td>
<td></td>
</tr>
<tr>
<td>methods:</td>
<td></td>
</tr>
<tr>
<td>• PowerDA</td>
<td>1</td>
</tr>
<tr>
<td>• PowerDA_LS</td>
<td>1</td>
</tr>
<tr>
<td>• PowerCC</td>
<td>2</td>
</tr>
<tr>
<td>Installation loop of PV and Wind</td>
<td>Each top 20 pixels</td>
</tr>
<tr>
<td>segments</td>
<td></td>
</tr>
<tr>
<td>Steps for installation [MW]</td>
<td>40</td>
</tr>
<tr>
<td>Year chosen for data</td>
<td>2009</td>
</tr>
<tr>
<td>Hub height for wind turbines</td>
<td>100m</td>
</tr>
<tr>
<td>PV orientation angles</td>
<td>From -90 to +90</td>
</tr>
<tr>
<td>PV tilt angles</td>
<td>From 0 to +90</td>
</tr>
<tr>
<td>Upper relative share of the residual</td>
<td>10%</td>
</tr>
<tr>
<td>load</td>
<td></td>
</tr>
<tr>
<td>PV potential [MW]</td>
<td>Germany: 379.7</td>
</tr>
<tr>
<td></td>
<td>Regions: Table 7</td>
</tr>
<tr>
<td>Wind potential [MW]</td>
<td>Germany: 94.76</td>
</tr>
</tbody>
</table>

|                                            |                                            |
| **Table 3: Assumptions and Pre-Set Values Used in the Model** |

After these assumptions and values are set and scenario defined, the program starts with generating the first set of different classes (combinations) of tilt and orientation angles, and getting the $19 \times 10 = 190$ possible combinations.

These correspond to the normalized PV time-series for which the program calculates the three allocation methods, which are the terms for the suitability factor formula discussed previously in Equations 10 and 11, and were the same applies to the normalized wind time-series.

These suitability factors are calculated and compared with one another to check for the highest value (the more suitable) each time for all installation steps in the program.

This highest value equals the maximum suitability factor of PV calculated over all pixels, and all tilt and orientation combinations. For wind, it equals the maximum suitability factor calculated over all pixels and for the chosen hub height of 100m.

To compare between the highest value of PV and wind, the following criteria is used:

\[
Is\ MaxPV > MaxWind
\]

Since we have 20 steps per loop (investigating the best 20 locations suitable for the installment of wind or PV capacity), then this condition gets tested 20 times in a loop, and then per each
4. The Model

answer, i.e.: MaxPV or MaxWind, a corresponding PV or wind segment gets installed, of 40 MW (or whatever step size is taken).

If MaxPV condition gets satisfied, the pixel with maximum suitability is used, and its corresponding tilt and orientation angle recorded, and then, the generation curve of this max tilt and orientation combination is loaded and the maximum generation curve extracted and used to downsize the residual load:

\[ \text{New residual load} = \text{previous residual load} - \text{generation curve} \times \text{step size} \]

The same applies for the MaxWind condition when it is satisfied.

At the end of this step, a test is run to see if there is further capacity on the pixel that was used, in which if the unused capacity is less than the step size the pixel’s value is put to zero, otherwise, the value of the suitability factor of the used pixel with its corresponding (combination of tilt and orientation or hub height) is set to zero meaning that it could be used again but not for the same combination that was chosen before (in case of PV). And the loop variable capacity step, PV segment, Wind segment gets increased correspondingly.
4. The Model

Real potential for each region, can be extracted from studies or assumed at an appropriate value

Figure 7: Main Inputs and Assumptions Used in the Model
Run equation-based functions and create matrices for the different allocation methods:
- CC: Correlation coefficient method
- CD: Covering the load method
- CDP: Covering the load peaks method

**PV generation timeline per location, tilt and orientation angles**

- Maximum CC for PV
- Maximum CCD for PV
- Maximum CDP for PV

**Wind generation timeline per location and hub height**

- Maximum CC for Wind
- Maximum CCD for Wind
- Maximum CDP for Wind

**Suitability factor for PV**

Choose best pixel of highest suitability factor

Reduce the residual load by adding the timeline of PV generation multiplied by the pre-selected step size

Save results for the new residual load and further parameters

**Suitability factor for Wind**

Choose best pixel of highest suitability factor

Reduce the residual load by adding the timeline of Wind generation multiplied by the pre-selected step size

Save results for the new residual load and further parameters

**Higher PV or Wind suitability factor**

**Figure 8: Model Steps to Simulate the Results**
5. Analysis of Germany as One Region

In order to implement the model described in the previous chapter and analyze the situation in Germany, certain assumptions have to be carefully made and values selected. The reason for this is the excessive run-time of the used code with a personal computer of a high speed and memory capacity which would last for approximately $4.5 \times 10^3$ days each time the program is run.

The objective in this chapter was to draw the baseline scenario for Germany without resorting to a location-oriented refitting, which will be the subject of the next chapter. This baseline scenario should give us an indication of the suitable sites for the installment of the available PV and wind capacity, and the degree to which the residual load is reduced by the installed capacity. The scenario shows the change affecting figures such as the correlation coefficient and the suitability factors.

In this simulation only half of the available capacity of the sum of both PV and wind was used, allowing us to use the better-half locations for allocating PV and wind plants.

The following values and assumptions in Table 4 were used to get the finalized results for the analysis of Germany as one region presented in this chapter.

<table>
<thead>
<tr>
<th>Germany</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pixels (Area covered)</td>
<td>3027 (around 348,672 km$^2$)</td>
</tr>
<tr>
<td>Load [TWh/year]</td>
<td>459.74</td>
</tr>
<tr>
<td>PV Potential [GW]</td>
<td>379.70</td>
</tr>
<tr>
<td>Wind Potential [GW]</td>
<td>94.76</td>
</tr>
<tr>
<td>PV : Wind</td>
<td>≈4:1</td>
</tr>
</tbody>
</table>

Table 4: Percentages of Load Coverage in Germany

As demonstrated in Table 4, the PV technical potential in Germany is four-times higher than that of wind. Matching should thus be made between where this potential is, and where it is suitable to install the different capacity available. For example, the installed wind and PV capacity by the end of 2010 were 27, 17.3 GW respectively (1.5:1 ratio). It would be interesting to see if the simulation results match this ratio.

Of course, with giving a bigger weight in the suitability factor formula for a certain method over another, this ratio could change. In this study, a higher weight was given for the allocating based on the correlation coefficient method as the model tries to put significance on this method for its smoothing effect consequences.

---

10 This value is up to ±20% correct
5. Analysis of Germany as One Region

5.1. Simulation Results

In the following table, some results for the simulation are shown:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>474.460</td>
<td>379.70</td>
<td>142.55</td>
<td>94.755</td>
<td>94.755</td>
<td>37.45%</td>
<td>100%</td>
<td>37.45%:63%</td>
<td>18.366</td>
<td>52,482</td>
<td>65%</td>
<td>1987</td>
<td>Half</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Simulation Results for Germany as One Region

In this simulation, half of the total available capacity from PV and wind was installed. We see that only 37.45% of the available PV capacity was installed, whereas the percentage is 100% for wind.

We also see that the PV share of the total generated energy of 298.850 TWh/year annually is 111.58 TWh/year or 37.33%. Then the PV:wind share of the whole generated capacity is approximately 37%:63%.

Moreover, it is important to assess the best locations for wind allocation by studying half the installed wind capacity, and these locations are shown later in Figure 14.

The residual load reduced to an average of 18,366 MW, a reduction of ≈ 65% from the 52,482 MW average it started with.

We note that the hours in which the residual load was below zero were 1987 hours and this can be seen also from the Residual Load Duration Curve (RLDC) shown in the following Figure 9, which indicates that:

- The average residual load is 48,220 MW for almost 1500 hours/year (≈ 17% of the time)
- The average residual load is 22,880 MW for almost 4980 hours/year (≈ 57% of the time)
- The average residual load is -19,870 MW for almost 1980 hours/year (≈ 23% of the time)
5. Analysis of Germany as One Region

5.1.1. PV Capacity Installed

As seen in Figure 10, much of the capacity has been concentrated in the western and southern regions rendering them the best location for PV installment according to the installment methods.

The maximum capacity installed was ≈784 MW in pixel number 1335, which corresponds to (7.1875 Lon. 51.5 Lat.) located in the western region.

The north-eastern region is almost empty, rendering it a highly non suitable region for PV installment, with only a few locations where capacity doesn’t exceed 100 MW.

The total PV capacity installed was 142,550 MW, which is 37.54% of the total available PV capacity in Germany.
5. Analysis of Germany as One Region

5.1.2. PV Capacity Installed Tilt Angles and Orientation Preferences

It is important to study the ideal orientation and tilt angles, and to compare these with the actual situation in PV plants in Germany. This will give an indication of the compatibility of the findings currently in place in Germany, as seen in Figure 12.

In Figure 11, it appears that the tilt angle of 70° and the orientation of 60° have the highest installed capacity. This is additionally shown in Figure 13, and compared with the actual situation in Germany.
5. Analysis of Germany as One Region

It is apparent that there is a difference between the actual situation in Germany for both the orientation and tilt angles in respect to their ideal positioning according to the simulation.
The results suggest an optimal tilt angle of 70°, and an ideal orientation angle of 60°, -10°, and -60°, in order of preference. The actual situation favors the tilt value of 32.5° as the maximum, as well as 47.5° and 22.5°. As for the orientation angle, the actual situation is obviously favoring 10° angle.

5.1.3. Wind Capacity Installed

Wind capacity is predominantly installed in the northern western and northern eastern regions, with very low capacity installed in the south east.

The maximum capacity installed is 855 MW, at (Lon. 8.9375 Lat. 54). However, this is not an accurate indication of the best locations for the installment of the capacity. Because all wind capacity has been installed we have to check for the best locations where half of the wind capacity (47,377 MW) was installed and see if these are the same locations that are proposed in Figure 13.

We can also decide on another value specified from Figure 15, like the step value at which the slope of installed wind capacity begins decreasing.
5. Analysis of Germany as One Region

The new figure for half the capacity installed is accordingly shown in Figure 14, white regions within the map represent those pixels with no wind potential.

Percentages of the installed capacity to the available capacity are used to give an indication of the installation order at half the installation steps of the full capacity.

Finally, Differences between installing the 47 GW to the available 94 GW are clear. For example, the maximum new capacity installed in this second case is 520 MW at the pixel number 282 (Lon. 7.4375 Lat. 53.625).

5.2. Discussion and Conclusion of the results

It is obvious from comparing Figure 5 to Figure 14 that all the available capacity from wind has been installed, highlighting the importance of differentiating at what point the differentiation between PV and wind stopped, as shown in Figure 15.

In Figure 16, the load demand is shown and plotted against the generation from both PV and wind capacity. The first plot in the upper location has the whole year time scale, i.e. 8760 hours. It is apparent that the load is not well covered in the first 1500 and last 1000 hours, the winter months in Germany, and that it is satisfactorily covered in other times, such as between 2000-3000 hours. The first observation is shown in the middle plot for the first 1000 hours (until around Mid-February). We can see few hours where peaks and loads are covered. By looking
5. Analysis of Germany as One Region

only at the plot, we can also see that good correlation is not prevalent although load peaks and generation peaks are more or less correlated together.

![Figure 15: Installation of PV and Wind Capacity](image)

In the last plot of Figure 16, which is between 2200-3000 hours, better results for load and load peaks coverage as well as the overall correlation coefficient are evident. We would expect these hours to have the better share of the below-zero residual load total at the end.

In Figure 17 we can see the overall change of the three allocation methods with installation steps. Several factors influence the shape of the decreasing suitability factor plot. For example, the sudden increase of load peaks coverage and better correlation with the load along rather constant load coverage after around 200 steps, high suitability factor prevails.

Keep in mind that these maximum values occur only for the first step in each loop which is defined by assigning the best top 20 locations, before next round of allocations, so sudden drops or changes in these trends should be expected.

Finally, we notice that the maximum residual load has not significantly decreased, only about \(\approx 7\%\) of the maximum residual load was decreased, but we notice that the average residual load has significantly decreased by about 65\%. There could be different reasons for that:

- This might be caused by the low weighing of the coverage the loads peak method.
- Might be due to certain particularly high peaks that could not be covered because of the non-existent PV-wind generation at the respective time-frame, so that the peak would never reduce by any of the allocation methods.

Next, we examine the regional results and identify the differences that exist in the overall residual load coverage and capacity installation when regions are created from the division of Germany.
5. Analysis of Germany as One Region

Figure 16: Different Time Ranges for Residual Load versus Generation Capacity for Germany
Figure 17: Allocation Methods Change for Germany and Suitability Factor Decrease in Analyzing These Different Results
6. Analysis of Germany Divided into Regions

New qualitative predictions can be deduced when dividing the whole set of Germany’s input data to newly created regions within it.

Six regions were hence developed to answer this study objective. Six regions present a random selection that is suitable for many considerations. It shows the difference between the western and eastern regions which have population density differences, Figure 18. The variation of PV and wind sources availability change also from north to south, Figure 5. And such a division has an ability to naturally accommodate an argument for further variances unaccounted for.

These regions mainly represent six known geographical directions: south-west or region one, mid-west or region two, north-west or region three, south-east or region four, mid-east or region five, and north-east or region six.

The objective thus for this division is to investigate the placement of capacity shift between the established regions in comparison with the distribution of these capacity for Germany as one region. This uncovers qualitative hints regarding storage capacity change and the needed transmission capacity.

After that, we would investigate how to limit the storage and transmission capacity. It is useful to have these regions because that allows us to study if the excess energy in any region can be reduced to compensate the losses that would occur due to the selection of the poorer sites, as in comparison with the Germany as one region scenario and with a reference scenario, that presents the expansions expected under the current conditions. Furthermore, the results can give us answers for such questions that may also arise:

Which locations exhibit the highest order for capacity installment...from wind sources…from PV sources? And how do the three allocation methods compare with each other in each of the regions...and with other regions?

And one may also ask: which regions are able to be a future energy exporter of energy to bring the residual load of Germany to a minimum...and which will act as an energy importer?

These and many other questions are certainly interesting to answer, such as the establishment of a national Direct-Current (DC) grid.

To answer questions concerning transmission and storage a basic transmission network model for energy exchange between the regions and a model of storage for the energy time shift is used section 6.2.
6. Analysis of Germany Divided into Regions

Table 6 describes numerically the number of pixels (or locations) in each region, the respective area, the population size, the PV and wind potential, and the load demand in each region. This load demand is linearly dependent on the population size.

Three indicators for PV and wind output are shown for half the used potential in each region: half capacity PV output, and half capacity wind output. Finally, the ratio between the full potential of PV to wind is presented.

<table>
<thead>
<tr>
<th></th>
<th>Reg. 1</th>
<th>Reg. 2</th>
<th>Reg. 3</th>
<th>Reg. 4</th>
<th>Reg. 5</th>
<th>Reg. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pixels</td>
<td>491</td>
<td>679</td>
<td>409</td>
<td>406</td>
<td>582</td>
<td>460</td>
</tr>
<tr>
<td>Area [Km²]</td>
<td>56,557</td>
<td>78,212</td>
<td>47,117</td>
<td>46,766</td>
<td>67,039</td>
<td>52,986</td>
</tr>
<tr>
<td>Population</td>
<td>17,503,702</td>
<td>28,365,287</td>
<td>8,644,355</td>
<td>9,490,845</td>
<td>11,308,329</td>
<td>7,050,544</td>
</tr>
<tr>
<td>PV Potential [GW]</td>
<td>63.2</td>
<td>112.0</td>
<td>47.7</td>
<td>40.6</td>
<td>77.7</td>
<td>38.7</td>
</tr>
<tr>
<td>Load [TWh/year]</td>
<td>97.7</td>
<td>158.3</td>
<td>48.3</td>
<td>53</td>
<td>63.1</td>
<td>39.4</td>
</tr>
<tr>
<td>PV : Wind (potential)</td>
<td>13.2:1</td>
<td>5.27:1</td>
<td>1.66:1</td>
<td>76:1</td>
<td>3.85:1</td>
<td>2.13:1</td>
</tr>
</tbody>
</table>

Table 6: Percentages of Load Coverage in Germany by the Six Newly Established Regions

In studying Table 6, a first rough estimation of the situation in the newly established regions is predicted. There is a high PV to wind potential that varies between the regions. However, this alone cannot explain to us the full picture; what we need to know is how much of this available potential from both PV and wind is optimally installed based on the energy allocation methods.

Also, we need to know which of the two sources will participate more in the 100% renewable share, and finally, whether this capacity will be able to cover the load demand at that region.

In the last row, we can see the ratio of the available PV potential in each region to the available wind potential. What we care for in this, is how much of this potential is actually suitable to optimally cover the load demand curve.

In Figure 18, the regions with the highest densities are predominantly in the south-west (region one) and mid-west (region two). This will have an effect on the coverage of the residual load in these regions if the sources available are not enough.
6. Analysis of Germany Divided into Regions

The maps were rescaled and show population densities up to 150,000 inhabitants per location.

Figure 18: The Six Regions with Population Densities in Colored Code

[Diagram showing population densities for the six regions of Germany]
6. Analysis of Germany Divided into Regions

6.1. Simulation model

6.1.1. Experimental framework

The six regions were created by allocating each set of data to its corresponding region, then, the main program designed for the analysis of Germany as one region was refitted to calculate the same results for each region.

Several new additions to the main algorithm were made to both optimize the results for Germany as one region and the six regions developed: The real potential of PV and wind plants from two different studies\(^\text{12}\) was used. Different trials were executed with different assumptions throughout the course of the research. These included using different step sizes (10MW, 25MW, 40MW, 50MW), the criteria was to have a realistic installation capacity, that’s able to distinguish the results for the optimal locations instead of using all the available locations, hence, a 40 MW installation step size was selected as the best choice.

This might have reduced the quality of the installed capacity allocation at a time but was necessary nonetheless to speed up the processing of the data by approximately 75%. This simply means that we install a plant of 40 MW at a suitable location instead of 10 MW or 50 MW, which is an acceptable size if our objective is a gross installation of wind and PV farms with high generation capacity.

The assumptions made for each region, are the same used for the treatment of Germany as a one region. The same data were also used, but by allocating each set of data to its corresponding region as mentioned earlier.

Due to the large size of data dealt with, different combinations, new sets of data that needed to be generated, and functions solved, processing time for each region took between 8-12 hours at a time and hence, minimizing processing time and having a proper memory size was a concern for the successful execution of the program with Matlab.

Finally, after the program is run and results simulated, two states at which the program stops running are: either half the available capacity is installed and the average residual load is less or equal to zero, or that half the available capacity is installed but the mean residual load is still bigger than zero.

---

\(^{12}\) These studies are cited in the references number 7 and 8
6. Analysis of Germany Divided into Regions

6.1.2. Simulation results

In Table 7, a summary of the main results is shown.

<table>
<thead>
<tr>
<th></th>
<th>South-West Reg. 1</th>
<th>Mid-West Reg. 2</th>
<th>North-West Reg. 3</th>
<th>South-East Reg. 4</th>
<th>Mid-East Reg. 5</th>
<th>North-East Reg. 6</th>
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<tr>
<td>Total capacity</td>
<td>67.98</td>
<td>133.22</td>
<td>76.44</td>
<td>41.37</td>
<td>97.83</td>
<td>56.86</td>
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<tr>
<td>available [GW]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total installed</td>
<td>34.01</td>
<td>66.61</td>
<td>38.76</td>
<td>21.13</td>
<td>49.07</td>
<td>28.43</td>
</tr>
<tr>
<td>capacity [GW]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity available PV</td>
<td>63.16</td>
<td>111.98</td>
<td>47.66</td>
<td>40.54</td>
<td>77.66</td>
<td>38.71</td>
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<tr>
<td>PV [GW]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total installed PV</td>
<td>29.19</td>
<td>45.88</td>
<td>11.96</td>
<td>20.29</td>
<td>28.90</td>
<td>11.37</td>
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<td>capacity PV [GW]</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Capacity available Wind [GW]</td>
<td>4.76</td>
<td>21.24</td>
<td>28.78</td>
<td>0.84</td>
<td>20.17</td>
<td>18.16</td>
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<tr>
<td>Total installed wind</td>
<td>4.76</td>
<td>21.24</td>
<td>28.78</td>
<td>0.84</td>
<td>20.17</td>
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<td></td>
<td></td>
<td></td>
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<td>Percentage PV installed</td>
<td>42.93%</td>
<td>40.97%</td>
<td>25.10%</td>
<td>50.05%</td>
<td>37.21%</td>
<td>29.36%</td>
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<td>Percentage Wind installed</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>96.69%</td>
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<tr>
<td>Average Load [MW]</td>
<td>11153.00</td>
<td>18074.00</td>
<td>5508.00</td>
<td>6047.60</td>
<td>7205.70</td>
<td>4492.60</td>
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<td>Percentage of Residual Load Reduced</td>
<td>30.96%</td>
<td>54.32%</td>
<td>139.50%</td>
<td>36.66%</td>
<td>106%</td>
<td>121.6%</td>
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<td>Residual load ≤ 0</td>
<td>643</td>
<td>1417</td>
<td>4894</td>
<td>1249</td>
<td>3819</td>
<td>4504</td>
</tr>
<tr>
<td>[Hours]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV:Wind Mix of Annual Generation TWh/Year [%]</td>
<td>77%:23%</td>
<td>47%:53%</td>
<td>16%:84%</td>
<td>91%:9%</td>
<td>38%:62%</td>
<td>22%:78%</td>
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<tr>
<td>Leading Source</td>
<td>PV</td>
<td>PV</td>
<td>WIND</td>
<td>PV</td>
<td>WIND</td>
<td>WIND</td>
</tr>
<tr>
<td>End state of</td>
<td>Half the total capacity installed</td>
<td>Half the total capacity installed</td>
<td>Average residual load less than zero</td>
<td>Half the total capacity installed</td>
<td>Average residual load less than zero</td>
<td>Average residual load less than zero</td>
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<tr>
<td>installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 Average Residual Loads and the Leading Source in Each Region after Installing Half the Available Capacity

The capacity available is the sum of all the available PV and wind provided in Table 6, where approximately, half of the available capacity was used as a criterion to distinguish properly the ideal top 50% of the available locations selected for capacity installment.
6. Analysis of Germany Divided into Regions

Following upon the experimental framework discussion, the end state of installation was average residual load less than zero (first end state) for regions 3, 5 and 6 and half the total capacity installed (second end-state) regions 1, 2 and 4.

We can also notice that it is mainly in these regions of high wind capacity installment where it is a leading source that we have the first end-state satisfied. The effect of installing PV capacity in regions where it is the leading source is mainly because wind capacity is not enough in that region and that’s when the second end-state prevails.

The percentage of residual load reduced is a measure of how well did the installed capacity manage in reducing the load demand in the respective region. The total new residual load is 141.773 TWh/Year for all regions, thus, the overall reduction in the residual load is 69.1%.

The leading source, gives us a sense of the predominant capacity type to be installed for the attainment of the stated reduction in the load demand in the respective region. However, it is seen clearly that wind prevails as a total sum of annual energy production in four of the six regions 2, 3, 5 and 6.

It is important to note in the last line, that the two end states describe how the processing of installing more capacity was done. First we see if the region can reach an average residual load of zero without using half of the capacity, and if so, we go on with installing the rest of the capacity. Otherwise, we install half of the capacity without reducing the average residual load below zero.

Next, based on the leading source in each region, regional results for the south-west, mid.-west, and south-east regions are presented for PV installed capacity. Also, optimal tilt and orientation angles setting for each region are presented and a comparison with the real tilt and orientation angles in place in Germany today made.

Finally, regional results are attained for the north-west, mid.-east and north-east regions for the wind capacity installed.

6.1.2.1. South-West region (Region One)

Following are three figures for the characteristics of the installed PV capacity in the south-west region (region one).

---

13 An exception was made to add this region to the wind analysis part due to its relatively close 1:1 ratio with the PV capacity installed and so, it would hold true for the argument in the wind section.
6. Analysis of Germany Divided into Regions

In Figure 19 we see the distribution of the installed PV capacity, and see where the maximum capacity was installed. For example we have a maximum of ≈ 500 MW at pixel 241 at the coordinate point (Lon. 9.1875 Lat. 48,875). However, the capacity installed is ≈ 60 MW on average per location.

Figure 19: Installed PV Capacity in the South-West Region

Figure 20: Orientation and Tilt angles for the Installed Capacity of Region One (South-West)
6. Analysis of Germany Divided into Regions

In Figure 20 and the explanatory Figure 21, we see that the tilt angle 70° and orient angles 70°, -10° and -70° were the mostly repeated angles for installation. This means that these angles are highly suitable for the installment of the PV capacity. However, it is clear that this doesn’t go in-line with what is in place in Germany today, with most frequently 32.5° used tilt angle and 10° orient angle.

6.1.2.2. Mid-West Region (Region two)

In Figure 22 we see again the distribution of the installed PV capacity, and get results for the maximum location, which is ≈ 784 MW at pixel 430, coordinate (Lon. 7, 1875 Lat. 51, 5). The installed capacity is ≈ 67 MW per each location on average.

In Figure 23 and the explanatory Figure 24, we see that in the mid-west region, tilt angle 50° and orient angle -10° were the mostly repeated angles for installation, meaning their high suitability for the installment of the PV capacity. However, it is clear that this doesn’t go in-line with what is being used in Germany today for tilt 32.5°, but which is close enough to Orient 10°.
6. Analysis of Germany Divided into Regions

Figure 22: Installed PV Capacity in the Mid-West Region

Figure 23: Orientation and Tilt angles for the Installed Capacity of Region Two (Mid-West)
6. Analysis of Germany Divided into Regions

Figure 24: Comparison between Frequency of Tilt and Orientation Angles used for the Different Installed PV Capacity in Region One (Mid-West)

6.1.2.3. South-East Region (Region four)

Figure 25: Installed PV Capacity in the South-East Region
6. Analysis of Germany Divided into Regions

Figure 26: Orientation and Tilt Angles for the Installed Capacity of Region Four (South-East)

Figure 27: Comparison between Frequency of Tilt and Orientation Angles used for the Different Installed PV Capacity in Region Four (South-East)
6. Analysis of Germany Divided into Regions

In Figure 25, we see once more the distribution of the installed PV capacity, and get results for the maximum location, which is \( \approx 778 \text{ MW} \) at pixel 97 at coordinate (Lon. 11,5625  Lat. 48,125) , the mean capacity installed is \( \approx 50 \text{ MW} \).

In Figure 26 and the explanatory Figure 30, we see that in the south-east region, two tilt angles 50° and 70°, and the orient angle -10° were the mostly repeated angles for installation, meaning their high suitability for the installment of the PV capacity. However, it is clear that this doesn’t go in-line with what is being used in Germany today for 32.5° tilt angle, but which is close enough to the Orient angle of 10°.

Next, we present the wind capacity for the other three regions, and naturally, we can compare between the maximum capacity installed, and more importantly, the percentage installed shown in Table 7.

6.1.2.4. North-West region (Region three)

![Figure 28: Installed Wind Capacity in the North-West Region](image)

In this region, the maximum capacity that was installed was \( \approx 520 \text{ MW} \), at the pixel number 257, at the coordinate point (Lon. 7, 4375 Lat. 53,625), with an average installed wind capacity of \( \approx 65 \text{ MW} \) per location.
6. Analysis of Germany Divided into Regions

6.1.2.5. Mid-East region (Region Five)

In this region, the maximum capacity that was installed was \(\approx 455\) MW, at the pixel number 439, at the coordinate point (Lon. 13, 5625 Lat. 51,875), and the average installed wind capacity per location is \(\approx 35\) MW.

6.1.2.6. North-East region (Region Six)
6. Analysis of Germany Divided into Regions

In this region, the maximum capacity that was installed was ≈390 MW, at the pixel number 78, at the coordinate point (Lon. 11, 9375 Lat. 52, 75) with an average capacity of ≈38 MW per location.

6.1.2.7. Selected suitability factors change with installation steps

In Figure 31, results are shown for the terms of the suitability factor in the first three plots; the correlation coefficient, load coverage, and the load peaks coverage methods. The fourth plot is the suitability factor itself, and the fifth plot shows the maximum residual load decrease with each installation step.

It can be seen that for the correlation coefficient (the same analysis applies for the load coverage and load peaks coverage methods), that the values the installation began with were well above 0.147 and then reduced in a fluctuating trend to -0.6538.

It can also be seen that the value of the correlation coefficient seems to locally increase at some points, which is probable; since the correlation coefficient values are renewed repeatedly per loop or top 20 locations found before the resetting of all the variables (maximum correlation coefficient, coverage of peaks, and coverage of residual load peaks).

In the final plot we see the sharp decrease of the residual load peaks at the beginning because of high wind influence for peaks reduction. Then the slower rate with installation steps after that because of the incapacity of PV to cover load peaks.
6. Analysis of Germany Divided into Regions

Figure 31: Allocation Methods Change for Region One and Suitability Factor Decrease in Analyzing the Different Results
6.1.3. Discussions and Conclusion of the Results of the Simulation Model

The effect of the available capacity of PV and wind on the maximum residual load reduction is evident as well as load peaks coverage rate. Figure 32 demonstrates this. At the installation step 373 almost all the wind capacity was installed and that is when the PV installation rate became increasingly linear and the wind capacity became constant. This situation however is not so for regions where there is almost an equal share of PV and Wind capacity, notably, the north-west, mid-east and north-east regions, this is shown in Figure 33.

![Figure 32: Installation Order for PV and Wind Shares in the South-West Region (Region One)](image)

![Figure 33: Installation Order for PV and Wind Shares in the North-East Region (Region Six)](image)
For the installed PV capacity, the tilt angles used are mainly, 70° and 50°, one reason is that with those angles we have a higher generation in winter and a lower generation in summer in comparison to tilt angles around 30°.

This means that the generation is more constant over the year, has better correlation with the load and produces less excess energy in summer where a higher percentage of load is covered. This however is quite different from the 32.5° tilt in place today in Germany.

This argument also holds true for the daily cycle where it is important not to produce excess energy at the day peak but to try and distribute the generation all over the day period and to match as much as possible with the load demand.

Using these optimized angles will reduce the storage needed daily and seasonally, which is an important consideration to take into account when studying the whole supply system.

The same argument holds true for the orientation angle, where the most frequent orient angle was -10°, which is relatively closer to the value of 10° degrees in place in Germany.

The main reasoning for this difference from the simulation results is that the simulation is based on a suitability factor that takes into account the whole system and, primarily, the correlation coefficient. At the other hand, it could be that planners are more interested in the bulk energy produced to benefit from the revenue of selling this energy without any consideration to the effect on the optimal reduction of the residual load.

**6.2. The Direct Current Load Flow Matrix – Transport Capacity**

To enable energy exchange between the six regions, a model of a Direct Current (DC) network is created, that connects the regions for the transportation of power in each hour to attain an hourly zero residual load.

It is important to consider a suitably sized storage and generator of energy at these hours in which it is impossible to overcome the residual load.

In this regard several possibilities or assumptions are made:

1- There is a large energy storage/generator that accommodates all the excess energy in a certain hour which can be used to generate this energy back when there is a lack of energy in another hour.

2- There is a certain transportation capacity which is based on the optimization of the maximum flow of energy in a certain hour.

3- A Direct Current Flow Load Matrix (DCFLM)\(^1\) determines the best path for the flow of energy based on the physical conditions that exist in the power flow lines.

\(^1\) See Appendix A
6. Analysis of Germany Divided into Regions

This division is random and rather academic in nature. This means that no consideration was given to the real network and generation capacity that is in place today. This is mainly because the objective of this study is not to optimize the currently established grid, but rather, to provide a sense of the optimal situation that future projects could follow and additionally provide a sense of the gross flow requirements.

In Figure 34, we see the six regions of Germany and the configuration of the power flow lines between the centers of the regions. Eleven lines that connect the regions together were suggested taking into consideration that a flow must happen at an economical and technically feasible basis. This is possible for a direct line connecting the most two adjacent centers of regions together without passing through a center of another region.

The possibilities then for export or import (based on each hour) from Region 1 to any location must be first to Regions 2, 5 or 4 respectively. If Region 1 is to export to region 6, this is to happen by flowing before in the lines of the other regions. This is because it doesn’t make sense to create a line specifically between region 1 and 6. This argument holds true for the other regions as well.

It must be noted however, that the DCLFM always passes a certain amount of power flow from any region to all regions, but these quantities differ and are a characteristic of the DCLFM as will be shown in the results later.

Figure 34: The DC Network between the Proposed Six Regions Shown According to their Geographical Orientation
In order to create this DCLFM, a storage location needs to be specified. Two options were possible: the first, in the middle of the map. The problem with this option is that it is feared that the power flow using the DCLFM will prefer a certain flow path through the storage node, which prohibits us from taking advantage of the full exchange of power between the regions before energy exchange between all regions.

The second option assumes a virtual storage based in a very distant location that will have the least favorable flow of power before the balancing takes place. The second option is therefore used. Table 8 shows the distances between the centers of the regions. The last two rows compare between the distance to the center of the map and the other - rather fictional - large distance storage point in the Atlantic Ocean! On which, the further analysis was based.

<table>
<thead>
<tr>
<th>Regions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Storage (S)</th>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
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</tr>
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<td>Storage (Central)</td>
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<td>2854,933</td>
<td>0</td>
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</table>

Table 8: Centrally Located Storage Scenario and DC Lines Distances (km)

After the optimization and shares of each source have been reached in the first step, the residual loads of the different regions are compared with one another and the hourly and yearly storage required calculated to have a total residual load equal to zero.

In Figure 37, the residual loads reached for each region are shown for the whole year where the line at the 0 MW residual load indicates the overall tendency of the region to be an energy exporter or importer. This of course can be validated later on by seeing the load flow direction and amount between the regions.

The hourly storage equals the summation of the total residual loads of the different regions:

\[ \sum_{reg=1}^{6} residualload of the six regions + residualload of storage = 0 \]

Figure 35 shows the residual load duration curve\(^{15}\) for the hourly storage capacity. By examining the dotted red line’s intersection with the x-axis, we see that for 2255 hours (~25% of the year) the regions are exporting power and for the other 75% of the time, power is being imported.

\(^{15}\) In section 6.2.1.1.1 a detailed definition and further examples of the residual load duration curve are given.
6. Analysis of Germany Divided into Regions

If we study the individual regions, we can understand where this percentage is coming from for each region. This is shown in Figure 36 where one can see the hour percentages which are positive.

Clearly, the higher this percentage is, the less is the region covering the residual load and the more it will tend to import energy from other regions first before taking it from the storage.

Figure 35: Residual Load Duration Curve for the Regional Storage

Figure 36: Hour Percentage where there is a Positive Residual Load per Region
6. Analysis of Germany Divided into Regions

Figure 37: Hourly Residual Loads for One Year, with Positive Residuals Above the Red Line and Negative Residuals Below it
6. Analysis of Germany Divided into Regions

6.2.1. The DCLFM and Load Flow Parameters

In Table 9 The DCLFM\(^\text{16}\) is defined showing the coefficients of flow in a set of buses (nodes) and lines, in our model, 7 buses and 17 lines are defined, generating a \((17 \times 7)\) matrix, two main inputs were provided to generate this matrix with the Matlab program, Bus and Line, moreover, other assumptions were also necessary for that\(^\text{10}\).

**Bus:**
- Number (from 0 to 6); where 0 is the storage point.
- Longitude and Latitude values for where each bus is positioned.

**Lines:**
- Number (from 0 to 6); where 0 is the storage point.
- Line direction: A definition of the line from its starting bus to its target bus.
- Length of lines in km

<table>
<thead>
<tr>
<th>Lines</th>
<th>From-To</th>
<th>Slack Node</th>
<th>South-West (1)</th>
<th>Mid-West (2)</th>
<th>North-West (3)</th>
<th>South-East (4)</th>
<th>Mid-East (5)</th>
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<td>-0.016</td>
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<td>-0.164</td>
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<td>0.166</td>
<td>0.165</td>
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<tr>
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<td>0.159</td>
<td>0.000</td>
<td>-0.005</td>
<td>-0.185</td>
</tr>
<tr>
<td>11</td>
<td>3-5</td>
<td>0</td>
<td>-0.067</td>
<td>0.004</td>
<td>0.284</td>
<td>-0.088</td>
<td>0.159</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>3-S</td>
<td>0</td>
<td>0.165</td>
<td>0.174</td>
<td>0.208</td>
<td>0.165</td>
<td>0.173</td>
<td>0.174</td>
</tr>
<tr>
<td>13</td>
<td>6-5</td>
<td>0</td>
<td>-0.073</td>
<td>-0.009</td>
<td>0.008</td>
<td>-0.093</td>
<td>0.159</td>
<td>0.339</td>
</tr>
<tr>
<td>14</td>
<td>6-S</td>
<td>0</td>
<td>0.146</td>
<td>0.153</td>
<td>0.154</td>
<td>0.146</td>
<td>0.154</td>
<td>0.189</td>
</tr>
<tr>
<td>15</td>
<td>5-4</td>
<td>0</td>
<td>-0.010</td>
<td>0.013</td>
<td>0.090</td>
<td>-0.389</td>
<td>0.193</td>
<td>0.102</td>
</tr>
<tr>
<td>16</td>
<td>5-S</td>
<td>0</td>
<td>0.156</td>
<td>0.157</td>
<td>0.156</td>
<td>0.159</td>
<td>0.174</td>
<td>0.157</td>
</tr>
<tr>
<td>17</td>
<td>4-S</td>
<td>0</td>
<td>0.160</td>
<td>0.159</td>
<td>0.152</td>
<td>0.192</td>
<td>0.162</td>
<td>0.152</td>
</tr>
</tbody>
</table>

Table 9: DCLFM Matrix for the Six Regions for a Distant Storage Configuration

In this matrix, rows represent the lines through which the power is flowing, and the columns represent the different regions. Several ways of reading this matrix are possible to fully understand how it works.

\(^{16}\) More details on the DCLFM can be found in appendix A
\(^{17}\) S = Storage node
6. Analysis of Germany Divided into Regions

- Firstly, if we look at the column South-East (region 4) for example, and sum vertically all the absolute numbers that belong to the lines of region 4 (circled), the summation of the absolute values should equal one (0.164+0.255+0.389+0.192 = 1). Other values in the same column provide other possibilities for the flow from or to region 4 but for significantly less values.

- Secondly, if we take the sum of each row, which represent each line, the value is approximately equal to zero, and if not, is set to zero by the summation with the slack node. The exception however is that the sum of each row in which storage is an element is equal to approximately one.

- Thirdly, the positive sign in each column indicate that the flow is in direction of the line definition as explained previously in the section.

To finally get the residual load flow between regions for each hour, the following equation is used:

\[
Load \ Flow(LF) = DCLFM \times Hourly\text{residualload for all regions and storage}
\]

Finally, after getting the [17 x 8760] LF matrix, several first indicators in Table 10 tell us how much is expected to be the capacity required per line, the storage to-from lines are omitted. These are the average flow per line, which we can use to optimize and select the optimal capacity requirements in each line through methods such as the residual load duration curves, next section’s topic.

<table>
<thead>
<tr>
<th>Line</th>
<th>Max [MW]</th>
<th>Mean [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9815</td>
<td>1624</td>
</tr>
<tr>
<td>2</td>
<td>7703</td>
<td>2367</td>
</tr>
<tr>
<td>3</td>
<td>2405</td>
<td>734</td>
</tr>
<tr>
<td>4</td>
<td>9065</td>
<td>3362</td>
</tr>
<tr>
<td>5</td>
<td>4990</td>
<td>2144</td>
</tr>
<tr>
<td>6</td>
<td>3261</td>
<td>1422</td>
</tr>
<tr>
<td>7</td>
<td>2002</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>420</td>
<td>-89</td>
</tr>
<tr>
<td>9</td>
<td>2025</td>
<td>-1362</td>
</tr>
<tr>
<td>10</td>
<td>1913</td>
<td>-1270</td>
</tr>
<tr>
<td>11</td>
<td>512</td>
<td>-1840</td>
</tr>
</tbody>
</table>

Table 10: LF Indicators for each Line

6.2.2. Duration Curves of the Transmission Performance (DCTP)

A DCTP or the RLDC term used in this context shows the relationship between the load flow capacity requirements and its utilization period. It becomes thus possible to eliminate the unnecessarily huge load flow requirements which take place for a limited duration of time.
The load flow is first ordered in descending order of magnitude, and at those points of curve inflection, the limitation and boundary values are taken.

Figure 38 shows the DCTP of line 1 (connecting region 1 to region 2), and the histogram in Figure 39 is also used, graphically displaying the DCTP and showing the frequency a certain capacity has been used.

With the arranged absolute values of the RL flow in line 1 used, we get that:

- The TP is always between 0 MW and ≈15300 MW.
- The TP is greater than 12000 MW for 1000 hours/year (≈11% of the time)
- The TP is between ≈6100 and 12000 MW for 5500 hours/year (≈63% of the time)

This is useful in giving us a sense of the utilization period of any capacity that we want to study, furthermore, and in order to complement the picture, the histogram in Figure 39 show us in an example for Line 1 how much a certain capacity range is utilized and what it is excluded.
It can be seen from the histogram and Table 11 that for line 1 and capacity over 6892 MW, the utilization time is 57 hours of the year (≈0.65% yearly). Which indicates that other transmission lines (detours in place of the direct path), or other measures like load management methods, at these hours, should be used to supply the lacking loads.

A refined result is thus reached by applying this concept on each line and setting a criteria for eliminating capacity at specified frequencies. First, all the possibilities for maximum capacity reduction are studied for all lines, and then an elimination percentage for each line is set. In general we can see a certain average elimination percentage for all lines less than ≈ 1.4%.

Finally, it must be noted, that for storage lines no refining or reduction in maximum flows are made, neither inclusion of their respective capacity because the lines connected to the storage are not used. They serve as an indication of the generation or consumption needs in each region.

<table>
<thead>
<tr>
<th>Line</th>
<th>Frequency of use over new maximum capacity</th>
<th>Percentage eliminated</th>
<th>Capacity new max or min limit [MW]</th>
<th>Max capacity [MW]</th>
<th>Min capacity [MW]</th>
<th>Capacity reduction percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>57</td>
<td>0.65%</td>
<td>6892</td>
<td>9815</td>
<td>-2607</td>
</tr>
<tr>
<td>2</td>
<td>1-5</td>
<td>59</td>
<td>0.67%</td>
<td>5903</td>
<td>7703</td>
<td>-1298</td>
</tr>
<tr>
<td>3</td>
<td>1-4</td>
<td>115</td>
<td>1.31%</td>
<td>1695</td>
<td>2405</td>
<td>-1146</td>
</tr>
<tr>
<td>5</td>
<td>2-3</td>
<td>54</td>
<td>0.62%</td>
<td>7828</td>
<td>9065</td>
<td>-3306</td>
</tr>
<tr>
<td>6</td>
<td>2-6</td>
<td>83</td>
<td>0.95%</td>
<td>4255</td>
<td>4990</td>
<td>-2355</td>
</tr>
<tr>
<td>7</td>
<td>2-5</td>
<td>2</td>
<td>0.02%</td>
<td>2729</td>
<td>3261</td>
<td>-2057</td>
</tr>
<tr>
<td>8</td>
<td>2-4</td>
<td>80</td>
<td>0.91%</td>
<td>3359</td>
<td>2002</td>
<td>-4699</td>
</tr>
<tr>
<td>10</td>
<td>3-6</td>
<td>14</td>
<td>0.16%</td>
<td>882</td>
<td>420</td>
<td>-1027</td>
</tr>
<tr>
<td>11</td>
<td>3-5</td>
<td>66</td>
<td>0.75%</td>
<td>4379</td>
<td>2025</td>
<td>-5091</td>
</tr>
<tr>
<td>13</td>
<td>6-5</td>
<td>74</td>
<td>0.84%</td>
<td>3372</td>
<td>1913</td>
<td>-3959</td>
</tr>
<tr>
<td>11</td>
<td>5-4</td>
<td>74</td>
<td>0.84%</td>
<td>-6984</td>
<td>512</td>
<td>-7799</td>
</tr>
</tbody>
</table>

Table 11: Optimization of Load Flow Capacity Requirements

It is necessary to recall that two storage models were suggested; the bypass (or large distance) storage model and the central storage model. In Appendix B the different results are shown for the central storage. We note that LF numbers are less for the lines passing from the regions to one another, meaning that the rest was exchanged with the storage. This proves our assumption that more capacity will pass through the storage node if it was put in the middle and that the central storage model should not be used for demonstration purposes.
The colored arrows are indicative only of the flow capacity in Table 11; the arrows on the circumference of the DC network are the storage’s generation peaks.
6. Analysis of Germany Divided into Regions

6.2.3. Discussions and Conclusions of the Results of the Transport Capacity

The situation regarding the coverage of the residual load and the ability of the different regions to be an energy importer or exporter of energy is concluded from Figures 36 and 37.

From these figures we see that the north-east, north-west and mid-east regions will act as energy exporters in the future.

The effect of the prevailing source can be clearly seen; with high wind capacity in the northern regions the residual load was brought to a minimum, while in these regions with low wind contribution, the residual load was on average much greater than zero.

A DCLFM was used to get the values for load flows in each line connecting the regions together in a grid. In order to see how much the fluctuation in storage is, two models were necessary to simulate for the storage, one which was central and one placed in a distant location. The large distance storage was used since results showed a greater summation of load flow exchanged between the regions before going to the storage. This value was 44,111 MW for the non–storage connected lines, for the large distance model and 29,362 MW for the central storage model which justifies using the large distance model.

A DCTP was used see the utilization period for any line and then to eliminate maximum capacity that are utilized for a low number of hours and for high capacity. In general the capacity eliminated was for utilization periods less than 1.4%, and this had a great effect on reducing maximum capacity requirements which were 59,813 MW in total and reduced to 48,278 MW, a reduction of $\approx 19\%$. 

7. Comparison with the Reference Scenario and Conclusions

A future reference scenario for Germany is presented, where installed PV capacity is given, for open spaces along railways, highways, and for roofs and facades. The overall capacity for the reference scenario was adapted to the six regions scenario. The allocation of the capacity shows an expected future situation, if the general conditions for the expansion of PV stay the same as today.

This reference scenario is compared with the scenarios presented earlier, namely: Germany divided into regions from chapter six and regions that were extracted from Germany as one region from chapter five.

7.1. Regional Scenario versus Reference Scenario

The reference scenario re-distributes the installed PV capacity in the six regions, based on the situation and conditions for PV in Germany today.

Figure 41: PV Generation Difference between the Installed Regional Capacity and the Reference Scenario
We see in Figure 41 that generally for each region new capacity was added to pixels that had no potential accounted for before, and that there is a decrease in the potential used for the reference scenario from what is used in the six regions scenario. Region 6 had particularly new potential added for in most pixels and opposed to region 1 that had more potential reduced in many pixels.

Since all wind potential was installed for all regions\(^\text{19}\), there was no need to compare the total capacity installed in each region with the other two scenarios.

The following table describes the differences between the installed PV capacity in this reference scenario and the regional scenario.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Region 1</td>
<td>29.12</td>
<td>29.19</td>
<td>99.8%</td>
<td>27.34</td>
<td>23.38</td>
<td>116.9%</td>
<td>85.95:14.15</td>
<td>85.98:14.02</td>
</tr>
<tr>
<td>Region 2</td>
<td>45.06</td>
<td>45.88</td>
<td>98.2%</td>
<td>39.02</td>
<td>40.51</td>
<td>96.32%</td>
<td>67.96:32.03</td>
<td>68.36:31.64</td>
</tr>
<tr>
<td>Region 3</td>
<td>17.54</td>
<td>11.96</td>
<td>146.7%</td>
<td>15.93</td>
<td>11.10</td>
<td>143.5%</td>
<td>37.87:62.13</td>
<td>29.36:70.64</td>
</tr>
<tr>
<td>Region 4</td>
<td>20.66</td>
<td>20.29</td>
<td>102%</td>
<td>19.25</td>
<td>17.66</td>
<td>109%</td>
<td>96.09:3.91</td>
<td>96.02:3.98</td>
</tr>
<tr>
<td>Region 5</td>
<td>23.1</td>
<td>28.90</td>
<td>80%</td>
<td>20.71</td>
<td>25.38</td>
<td>81.6%</td>
<td>53.39:46.61</td>
<td>58.90:41.00</td>
</tr>
<tr>
<td>Region 6</td>
<td>12.14</td>
<td>11.37</td>
<td>107%</td>
<td>11.31</td>
<td>10.46</td>
<td>108.1%</td>
<td>40.88:59.12</td>
<td>39.30:60.70</td>
</tr>
</tbody>
</table>

Table 12: Differences in Installed PV Capacity between the Reference Scenario and Simulation Results for the Six Regions

We generally see the good matching between the PV potential used and the newly provided PV potential from the reference scenario. This is particularly true for regions 1, 2, 4 and 6. The last two scenarios show the PV to wind share of installed power per region for both scenarios.

Next, we shall investigate the reference scenario’s effect on the line capacity requirements.

We see in Table 13 that the maximum flow requirements are 12.33% more for the reference scenario but with almost no change to the mean flow requirements between the two scenarios. We also see that the flow direction is the same for all maximum flows but is reversed for the mean flow through lines 8, 9, and 10.

The difference in the maximum capacity requirements is calculated by subtraction of the maximum flow of the reference scenario from the regional scenario showing that the value for the reference scenario is higher by 6208 MW.

\(^{19}\) Except for region 6 where it is 96.7%
Table 13: Differences in Installed PV Capacity between the Reference and Six Regions Scenarios

Finally, the theoretical accumulated storage was calculated for both scenarios and was found to be 141.737 TWh for the regional scenario and 144.374 TWh for the reference scenario increasing the storage requirements.

7.2. Regional Scenario versus Germany as One Region Scenario
Table 14 compares between the installed capacity in Germany as one region scenario and the regional scenario.

Table 14: Differences in installed PV Capacity between Germany as One Region Scenario and Simulation Results for the Six Regions

---

20 The value for each region in this row was calculated by dividing the percentage of the PV plants installed in GW from the total installed by the total sum of the PV generated power per year for Germany unlike Table 12 for the reference scenario where it was extracted directly from the given input data.
A bigger difference is clearly seen between the capacity installed in Germany as one region scenario and the regional scenario, this is obvious for region 6 (north-east) where in the one region scenario almost no PV capacity is installed in comparison with the regional scenario with 99.4% less capacity installed in the Germany as one region scenario.

As in the first comparison, we compare in Table 15 between the differences affecting the maximum and mean load flow in each of the two scenarios investigated.

<table>
<thead>
<tr>
<th>Line</th>
<th>Max (Ger./Sim.) [MW]</th>
<th>Difference (Sim. – Ger.) ±[ MW]</th>
<th>Mean (Ger./Sim.) [MW]</th>
<th>Difference ±[ MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10030</td>
<td>-215</td>
<td>1838</td>
<td>-214</td>
</tr>
<tr>
<td>2</td>
<td>6743</td>
<td>960</td>
<td>2286</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>2788</td>
<td>-383</td>
<td>937</td>
<td>-203</td>
</tr>
<tr>
<td>4</td>
<td>10820</td>
<td>-1755</td>
<td>3235</td>
<td>128</td>
</tr>
<tr>
<td>5</td>
<td>6548</td>
<td>-1558</td>
<td>1770</td>
<td>374</td>
</tr>
<tr>
<td>6</td>
<td>4952</td>
<td>-1691</td>
<td>1144</td>
<td>278</td>
</tr>
<tr>
<td>7</td>
<td>4696</td>
<td>-2694</td>
<td>162</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>2243</td>
<td>-1823</td>
<td>-280</td>
<td>191</td>
</tr>
<tr>
<td>9</td>
<td>3546</td>
<td>-1521</td>
<td>-1509</td>
<td>147</td>
</tr>
<tr>
<td>10</td>
<td>3618</td>
<td>-1704</td>
<td>-1077</td>
<td>-194</td>
</tr>
<tr>
<td>11</td>
<td>4792</td>
<td>-4279</td>
<td>-1210</td>
<td>-630</td>
</tr>
<tr>
<td>SUM</td>
<td>60775</td>
<td>-16663</td>
<td>15449</td>
<td>764</td>
</tr>
</tbody>
</table>

Table 15: Differences in Installed PV Capacity between Germany as One Region Scenario and Simulation Results for Six Regions

Note in Table 15, that there has been no sign change for the lines direction already introduced in the previous chapter, but that the direction has changed for the mean flows through lines 8,9,10 and 11, for both scenarios.

The sum value shows the sum of the maximum and the mean load flow capacity for all lines, for each the reference scenario and the simulation scenario. The difference between the simulation result and the reference scenario is calculated. We see a clear difference of -16,663 MW for the maximum capacity and 764 MW increase for the mean value. Finally, the percentages show this reduction for the maximum capacity, and increase for the mean value.

Finally, the theoretical accumulated storage was calculated again these two scenarios and was found to be 141.737 TWh for the regional scenario and 160.850 TWh for the reference scenario increasing by almost 13% the storage requirements.
7.3. Conclusions of the Comparison

The redistribution of PV capacity in the reference scenario affected matching between the two scenarios with regards to the capacity installed, and energy generated yearly.

Also, maximum flow capacity for all lines increased by 12.33% with the reference scenario, meaning that the regional scenario has less capacity requirements for lines and thus is a better scenario for load flow since the requirements for capacity are less. There was almost no change on the mean flow for both scenarios and thus no preference can be based on this aspect.

Taking the comparison with Germany as one region scenario, we see that the overall capacity installed is more in the regional model, which when summed up is 147.59 GW for the six regions scenario and is 142.54 GW for the Germany as one region scenario.

When we redistribute capacity for Germany as one region to match the regional model, load flow requirements increase by a significant 27% for the maximum flow and reduced by almost 5% for the mean flow. And so, it is even clearer in comparing with this scenario that less flow capacity is needed with the Germany as one region division to regions than having a Germany as one region scenario. Accordingly, it is useful to study regions and have it as a focus point to study further regional arrangements.

If we compare between results of the reference scenario to the Germany as one region scenario, we see that the reference scenario installs more PV in the regions providing less flow requirements, this indicates the better distribution of PV capacity in the reference scenario in comparison with the Germany as one region scenario.

When taking the storage requirements we can see the advantage of the regional scenario as it reduces by around 2% and 13% the storage requirements in the reference scenario and the Germany as one region scenario consecutively.
Finally, figures for the conclusions made thus far are summarized in Table 16.

<table>
<thead>
<tr>
<th></th>
<th>Regional scenario</th>
<th>Reference Scenario</th>
<th>Germany as one region scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total PV Potential [GW]</strong></td>
<td>147.95</td>
<td>147.62</td>
<td>142.54</td>
</tr>
<tr>
<td>PV Potential Reg./Other scenario</td>
<td>-</td>
<td>-0.22%</td>
<td>-3.66%</td>
</tr>
<tr>
<td><strong>Total PV generation [TWh/year]</strong></td>
<td>128.5</td>
<td>133.56</td>
<td>111.58</td>
</tr>
<tr>
<td>PV:Wind in annual generation %</td>
<td>40.39%</td>
<td>41.63%</td>
<td>37.33%</td>
</tr>
<tr>
<td>LF/Reg.</td>
<td>+12.33%</td>
<td>+27.42%</td>
<td></td>
</tr>
<tr>
<td>% Load covered</td>
<td>69.18%</td>
<td>69.79%</td>
<td>65.01%</td>
</tr>
<tr>
<td><strong>Storage Size [TWh/year]</strong></td>
<td>141.736934</td>
<td>144.374350</td>
<td>160.850210</td>
</tr>
<tr>
<td>% Storage requirements/Reg. scenario</td>
<td>+1.86%</td>
<td>+13.48%</td>
<td></td>
</tr>
</tbody>
</table>

Table 16: Summary of Main Conclusions between the Regional Scenario and the Reference Scenario as well as Between the Regional Scenario and Germany as One Region Scenario

We notice that this has an effect on the total load demand coverage to be 69.79% for the reference scenario, slightly more than the 69.18% for the regional scenario because for the reference scenario the orientation of PV panels is optimized to generate the maximum yield without giving consideration to what’s best for the whole supply structure.
8. Case study: Morocco

Morocco has a high potential in both, wind with a 1188 TWh/year technical potential, and solar power with a Global Horizontal Irradiance (GHI) for PV of 2000 kWh/m²/year \[11\].

The purpose of this chapter is to demonstrate the rough figures on reducing the average residual load to a zero by installing PV and wind capacity through the allocation methods.

Due to the lack of available detailed data, in contrary to the analysis for Germany, 60 locations were chosen in the country where 60 solar and 51 wind data normalized generation time-series were extracted, and in so doing, the study reduced to only common 51 points. This meant that independent scenarios for PV and wind are looked-for. This is shown in Figure 42.

![Figure 42: Selected Points for PV (Black-Dispersed) and Wind (Green-Concentrated)](image-url)
8.1. Data

8.1.1. Solar Data
The solar data for the year 2005 was extracted per pixel from the SODA (Solar Energy Services for Professionals) database on their website for 60 locations in Morocco\(^{12}\).

The solar data for Morocco extracted from the SoDa website were: the hourly mean clear sky model and the global horizontal irradiance as well as the ambient temperatures.

The data was processed and normalized time-series for the different tilt and orientation angles developed with the Matlab program\(^{13}\).

8.1.2. Wind data\(^{14}\)

Wind data that covers the range of [7km x 7km] area was extracted from the COSMO-EU data, after that, this large set of data was calculated near the chosen coordinates of the PV since it determined the number of locations to be studied.

The methodology is based on a physical model with modeled wind fields from a numerical weather prediction model as a starting point. It includes reductions of wind speed and power outputs due to shading effects, grid losses and availability as well as assumptions about future hub heights, future power curves, the dismantling of older wind turbines and their replacement by modern turbines and the additional reduction of the availability of offshore wind farms on stormy days.

For this particular case, average wind speeds at the common PV-Wind points were taken, and the power curve at each point generated, normalized power time-series for these points, Figure 43 show the power curve at the coordinate point (Long. -9,17 Lat. 28,66).

![Figure 43: Power Curves at a Specified Location in Morocco](image-url)
The power curve was made by a convolution of the original power curve (of a MM92-turbine) with a Gaussian distribution with a standard deviation of [0, 1 x wind speed]. The convoluted power curve leads to a smoother shape of the power curve, and in doing this we model the spatial distribution of the turbines within a pixel. The more turbines we have within a pixel the smoother the "pixel-power curve" should be.

The hub height used and measurements taken were at an altitude of 100m. The turbine REpower MM92, and wind speed values were taken every 1 hour. The power output was reduced by 5% due to electrical losses and turbine failures.

Finally, the nominal power of the MM92-turbine is 2 MW. And the smoothing of the power curve seen in Figure 44 is the "multi-turbine power curve"[15].

8.1.3. The load curve
As shown in Figure 44, the load curve of Morocco - provided by ONE [16] - is significantly less than that of Germany. Several indicators for this significance are given in Table 17.

Figure 44: The Load Curve of Germany and Morocco for 2009 and 2010 Respectively
8. Case study: Morocco

We see from the Figure 44 and Table 17 the huge difference between the two load curves, and this would definitely affect the simulation results for Morocco.

<table>
<thead>
<tr>
<th></th>
<th>Morocco</th>
<th>Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Peak GW</td>
<td>5.35</td>
<td>74.464</td>
</tr>
<tr>
<td>Load Mean GW</td>
<td>3.142</td>
<td>52.482</td>
</tr>
<tr>
<td>Yearly Load TWh/Year</td>
<td>27.523</td>
<td>460</td>
</tr>
<tr>
<td>High Peak [day]</td>
<td>12.08</td>
<td>19.01 &amp; 21.11</td>
</tr>
<tr>
<td>Low peak [day]</td>
<td>19.11</td>
<td>6.03 &amp; 13.04</td>
</tr>
</tbody>
</table>

Table 17: Load Demand Characteristics in Morocco and Germany

8.2. Experimental Framework

The aim of the study was to see the capacity required to cover 100% average residual load by each source independent of the other. This objective was set as we do not have an equal number of data points for both PV and wind.

The scenarios developed to demonstrate the results for each source will depend directly upon the factors used in the suitability factor formula. These factors are shown in Table 15 for both scenarios.

Taken the area of Morocco, the assumption made for the wind potential in each ≈7700 km² is set at a safe 1000 MW.

As for PV, with more pixels to study, each location covered a range of ≈7500km² and was set also at 1000 MW PV potential per location.

Weighing the three allocation methods for wind produced three scenarios. This allows us to understand which factors contribute the best in covering the residual load with the least capacity installed. The third allocation method for PV was omitted from the calculations as will be explained in section 8.3.2

The following table shows the different scenarios, Table 18.

<table>
<thead>
<tr>
<th></th>
<th>Wind scenario</th>
<th>PV scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient's power (PowerCC_PV)</td>
<td>W_A (3,1,1)</td>
<td>PV_A(3,1)</td>
</tr>
<tr>
<td>Covering the load power (PowerDA)</td>
<td>W_B (1,3,1)</td>
<td>PV_A(1,3)</td>
</tr>
<tr>
<td>Covering the residual peak power (PowerDA_LS)</td>
<td>W_C (1,1,3)</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 18: Scenarios for the Coverage of the Residual Load of Morocco by PV and Wind
8.3. Simulation

8.3.1. Wind Scenarios

The results show a consistent installed wind capacity of 12,250 MW that brings the average residual load to near a zero value, moreover, the hours in which the residual load is less than zero were around 3,410, or around \( \approx 40\% \) of the time for the three methods.

Table 16 shows a summary of the results for the three methods. Figure 45 shows the locations for the installation of wind capacity for scenario W_A. Figure 46 shows the wind generation versus load demand.

<table>
<thead>
<tr>
<th></th>
<th>W_A</th>
<th>W_B</th>
<th>W_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed wind capacity [MW]</td>
<td>12250</td>
<td>12530</td>
<td>12250</td>
</tr>
<tr>
<td>Average residual load [MW]</td>
<td>-1,964</td>
<td>-0,604</td>
<td>-1,435</td>
</tr>
<tr>
<td>Hours where residual ( \leq 0 )</td>
<td>3418</td>
<td>3411</td>
<td>3407</td>
</tr>
<tr>
<td>Peak residual load reduced</td>
<td>( \approx 7% )</td>
<td>( \approx 7% )</td>
<td>( \approx 7% )</td>
</tr>
</tbody>
</table>

Table 19: Summary of Wind Scenario Results

![Figure 45: Installed Wind Capacity for Morocco](image)
It is shown, that the eastern region has good pixels for the installation of wind capacity, but this doesn’t tell if there are barriers to the installation of wind farms in those regions, as the real potential is not known. Also, the north-western region is an adequate location for the installation of wind capacity.

![100% Wind Scenario](image)

**Figure 46: 100% Wind Share Scenario for the Coverage of the Residual Load of Morocco**

In Figure 46, we see that a 100% wind scenario only, has no coverage over the summer period, and an excessive coverage between 44-48 weeks. This would require high storage and transfer capacity.

### 8.3.2. PV scenarios

If we are to take the generated power from PV alone, we must first realize that the fluctuation of this source is diurnal, with a trend of increased generation during summer time, and that no generation is available during night time.

This means, that no matter how much we install PV capacity, it will not serve our objective of reaching a zero residual load when for times with no PV generation. All the extra capacity installed would not be required during the load demand hours, unless we have enough storage to supply this energy at night or transfer mechanism for this energy with neighbouring countries.

The analysis here is only concerned with presenting rough values for the capacity needed to reach a zero residual load mean, and another figure for how much capacity is needed if no storage or transfer capacity is available. For that, a step size of 40 MW was chosen.
Additionally, discussion about the ideal installation angles (tilt and orient) is presented, as well as the ideal locations for this installation.

Only two of the three allocation methods were used, namely: the correlation coefficient method and covering the load method. The contribution of the load peaks coverage is not an objective to investigate in this scenario, as the peak is falling in a time period with no PV generation, which renders it impossible to reduce.

Figure 47 explains the impossibility of covering loads and load peaks at regions where there is no PV generation and the inherent need to mix with other renewable sources, storage or transfer.

As can be seen, less installed capacity is required with more emphasis on covering the load method, this is obvious, as the correlation will be somehow constant and rising the term of the correlation coefficient to the power three will not increase the load covered.

<table>
<thead>
<tr>
<th></th>
<th>PV_A (CC^3)</th>
<th>PV_B (DA_PV^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed PV capacity [MW]</td>
<td>25560</td>
<td>19520</td>
</tr>
<tr>
<td>Average residual load [MW]</td>
<td>-4.2</td>
<td>-2.5</td>
</tr>
<tr>
<td>Hours where residual &lt;= 0</td>
<td>3842</td>
<td>3722</td>
</tr>
<tr>
<td>Peak residual load reduced</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Table 20: Comparison between the Two PV Results Based on Different Weighing Factors
8. Case study: Morocco

Table 20 shows the difference in the installed PV capacity per each method weight. The PV_A has the correlation coefficient power equal 3 and a load coverage power equal to 1. While the PV_B scenario has a load coverage power of 3 and a correlation coefficient power equal to 1. In the coming figures, results for PV_B scenario are displayed.

In Figure 48, we can see the locations of the installed PV capacity, these are primarily in the south west, and north east regions.

![Figure 48: Installed PV Capacity of 19520 that is Able to Bring the Mean Residual Load to Zero](image)

However, more regions in the northern west locations were also suitable according to the installation methods and factors used.

In Figures 49 and 50, we see the ideal tilt and orientation angles were the highest frequent tilt and orient angles were 50° and 80° respectively.
8. Case study: Morocco

In Figure 51, the weekly average PV generation curve that is able to overcome 100% residual load by PV only is shown in the figure. Keep in mind that the values for both PV and the load demand are averaged on weekly basis, and so, we cannot see the no-generation periods of PV on daily basis.
8. Case study: Morocco

We see from the figure that PV generation is highest between the 20\textsuperscript{th} and 30\textsuperscript{th} weeks, which occur in summer and is lowest in winter. There is a slight correlation with the load which experiences a peak between the 33\textsuperscript{rd} and 40\textsuperscript{th} weeks.

![Figure 51: PV Generation Curve for a 100% PV Scenario](image)

8.3.3. Storage Requirements

![Figure 52: Hourly Theoretical Accumulated Storage for PV and Wind](image)
In Figure 52 the theoretical needed storage size is found out by summing up the storage or generation needed from the previous hour with the current hour. Two theoretical sizes were found for the PV and wind models. The size for PV size is 2.008602 TWh and for wind is 2.552547 TWh.

As we can see in Figure 53, there is a clear difference between the uniformity of storage requirements for PV and wind, it is clear for PV that during summer months there is an excess of energy generation and a lack thereof during winter. The maximum daily stored or discharged energy was calculated and found to be 45,147 MW\(\cdot\)h/day and a maximum monthly stored or discharged energy of 803,011 MW\(\cdot\)h/month. The range between this maximum and minimum storage or discharge required is 45,108 MW\(\cdot\)h/day and 710,123 MW\(\cdot\)h/month respectively.

The sum of stored and discharged energy during the whole year for PV is 14,371,104 MWh/year and 14,407,975 MWh/year respectively, which leads to the hourly average -2.5 MW residual load.

For wind, there is less uniform storage or discharge utilization temporally. The maximum daily stored or discharged energy is found to be 189,022 MWh/day and a maximum monthly stored or discharged energy of 1,452,732 MWh/month. The range between this maximum and minimum storage or discharge required is 188,811 MWh/day and 1,438,623 MWh/month respectively.

The sum of stored and discharged energy during the whole year for wind is 10,589,109 MWh/year and 10,606,316 MWh/year respectively, which leads to the hourly average -1.96 MW residual load.
Discussion of the results and conclusions

In comparing the three wind scenarios together, no clear conclusions could be made about the effect of the allocation methods factors. This is mainly due to the rough estimation of wind potential available at each site, and gross size of the pixels used.

For a wind-only scenario, a capacity of 12,250 MW will be needed to cover the residual load, however, this doesn’t take into account the storage needed to supplement the needed energy at times of no wind generation, i.e. week numbers 7 and 24-36.

The 100% PV scenario was studied and the least capacity needed to cover the residual load is by using the coverage of the load term to equal 3. This can be understood, as our aim is to cover the mean residual load as a bulk quantity, whereas the correlation coefficient only looks at the correlation between PV generation and load at each hour.

For the selected PV-only scenario, a capacity of 19,520 MW will be needed. The argument that this capacity is not well dispersed to match the load curve stands as well, and renders this figure much higher than the actual needed, because storage will be needed to store the excess capacity at day time and transfer it at night time to the grid.

From the storage requirements, it is clear that storage in summer is needed for the PV scenario to supplement it in winter. This cannot be clearly concluded for wind due to the dispersion of generation throughout the year, although there is a general trend of increased generation when PV is lacking generation, i.e. during winter months.

The ratio between storage requirements for PV based on the total sum of energy stored or discharged daily is only 24% of wind daily storage requirements, but when calculated monthly becomes 55% of the wind monthly storage requirements, finally, these storage requirements become 136% more for PV yearly storage than yearly wind storage requirements. We conclude that daily storage for PV is favorable to compensate the day and night gap, and that a large yearly or seasonal capacity storage for wind would be a better storage solution for the wind scenario.

We notice from Figure 52 that the accumulated storage requirements for PV are less than for wind with a max of 1611788 MW for PV and -1695790 for wind.
9. Conclusions and Recommendations for Further Research

9.1. Conclusions

According to current assumptions, the PV potential is higher than wind in Germany; the total available PV potential in this study is around 380 GW, while it is 95 GW for wind. With further development of the technique, declining prices and change in regulations, the usable potential for wind may increase.

Both sources are able to overcome a significant part of the mean residual load and reduce it by around 65% when installing only half of their available capacity of 237.500 GW with a total yearly generation of 298.880 TWh/year. However, only 7% of the maximum residual load is reduced mainly due to the incidence of the load demand peaks at time periods with no suitable PV or wind power generation.

Installing half the total capacity for both sources resulted in installing the full wind potential and only 37.45% PV potential.

Most of the installed PV capacity was in the west, south and south-east regions, because there are more buildings and more highways and railways and thus more potential. As for wind, the north-western region dominated the installed wind capacity.

The most frequently used tilt angle in the Germany as one region scenario was 70° and were 60°, -10° and -60° for orient angle. This deviates from the situation in place nowadays in Germany, were PV tilt angles are frequently set at 32.5° and the orient angle on the other hand is set at 10°. The main reason for this deviation is that energy producers put more emphasis on the bulk energy generated by PV modules than other considerations accounted for in this study, which looks at the supply structure, its correlation with the load demand, and the distribution of the load coverage daily and seasonally, this eventually reduces storage and transmission capacity.

When Germany is divided into regions, it becomes possible to see how the new regions reduce the load demand, increasing the coverage of the mean residual load to 69.18%. The total yearly generation was found to be 318.049 TWh/year, 6.4% more than the Germany as one region model.

According to the definition of the regions, the south-west, mid-west and south-east regions were able to reduce the mean residual load by 31%, 54% and 37% respectively. The main source installed in these regions was PV. The angles installed in each region also differed than what is
9. Conclusions

in place nowadays in Germany. However, different regions exhibit different “ideal” tilt and orientation angles.

Wind energy is the leading source installed in the north-east and north-west regions, it is also considered to be the leading source in the mid-east region. In these regions, as the situation in Germany as one region, all the available wind potential was installed.

With almost 139% reduction in the mean residual load, the north-west region will be an energy exporter in a 100% PV-wind energy scenario. The north-east and mid-east regions will also play this role. This can be read in combination with the low load demand due to the less population density, particularly in the north-west and north-east regions.

Transport and storage capacities are possible to model for the regional scenario. Based on the storage duration curve, we can see that during 25% of the time, energy is being exported from the regions while it is being transferred to the regions for the other 75% of the time. A grid connecting the centers of the regions was created using the DCLFM to export and import energy first between the regions before all the excess or lack energy gets exported or transported to the ideal storage/generator. From the load flow in each line, the range of line capacity is between 800 MW and 7800 MW; the minimum and maximum values of load flow through the DC grid.

Two scenarios were used to compare the load flow requirements and PV capacity installed in the regional scenario to provide concrete answers to whether our objective is achieved of predicting qualitative indicators of load coverage and PV-wind installation by the regional model.

In both cases, the maximum flow requirements were less in the regional model by 12% and 27% than for the first reference scenario and the second Germany as one region scenario. The storage size was found to be 160.850 TWh and 144.374 TWh for the Germany as one region scenario and the reference scenario respectively. This is higher by 13% and 2% than the 141.737 TWh storage capacity calculated for the regional model. These results for the storage and transmission requirements have proved the advantage of using the regional model analysis to reduce both the storage and transmission requirements.

The PV share from the total installed capacity was 41.63%, 40.39% and 37.33% for the reference scenario, regional scenario and Germany as one region scenario respectively. The total load coverage was most for the reference scenario because of the higher energy yield with a value of 69.79% slightly higher than the regional scenario with a value of 69.18%. The total load coverage for Germany as one region scenario is found to be 65.01% owing to the fact that less PV was installed.

Based on these results, we conclude that further divisions in the map of Germany is advantageous to study the ideal positioning of PV and wind capacity as well as further reducing transport and storage capacity as well as the mean residual load.
In Morocco case study, 1000 MW for each PV and wind source potential was able to overcome the mean residual load by a 100% PV scenario and by another 100% wind scenario. For wind, 12,250 MW were installed to meet the mean residual load. For PV, the installed capacity value was 20 GW when a bigger weight was given for covering the load factor and was 25 GW when the weight was bigger for the correlation with the load factor. The most frequent PV tilt and orient angles for the 20 GW capacity are 50°, 80° for tilt and 90°, -90° for orient angles.

Although less capacity was needed to overcome the mean load by wind, more storage capacity is needed and was found to be 2.553 TWh, exceeding by 27% the requirement for PV storage of 2.009 TWh.

9.2. Recommendations for Further Research

- Investigating the temporal impact by using input from more than one year
- More renewable energy sources must be included, this study only focused on the fluctuating sources PV and wind, however, other sources such as Bio-energy and Geothermal energy could play a role in providing a coverage of the base load and contribute to better assessment of load demand coverage possibilities and reducing the required storage and transportation capacity.
- More regions, and a new configuration and division of these regions, must be studied in order to approximate the reality and get a better estimation of the loads in each new region, the available capacity to cover this load, and to ideally place PV, wind and other RES capacity.
- The weighing of the suitability factor formula terms must be optimized and studied for each RES in the study, so that the objectives of integrating each RES are properly fulfilled.
- Considering further criteria for the suitability factor, e.g. transmission capacity and gradients of the residual load.
- Study new and various DC connections between the regions, and study in details the losses incurred, and better estimation of the capacity limits in each line.
- Study the real technical requirements for storage and find the best locations for them.
References


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[10] Fraunhofer-Institute, Kassel-Germany, Contact person: Mareike Jentsch


[13] Fraunhofer-Institute, Kassel-Germany, Contact person: Kaspar Knorr


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Appendices

Appendix A: DC Load Flow

DC load flow is a method to estimate power flows through lines on AC power systems. The following is a brief introduction to the main concept of the power flow used in this study.

A "DC" load flow uses a simplified, linear form of modelling the AC system. Consequently its solution is non-iterative, and absolutely convergent. It becomes a routine algebra problem, solving multiple equations with multiple variables. It is inherently less accurate than a "full" AC load flow solution, but it is useful where fast, dependable solutions are essential, and the approximation is acceptable.

In reality, there is nothing "DC" about a DC load flow. It solves for phase angles (an AC, reactive characteristic); it ignores resistance (a DC characteristic); and it ignores voltage (because the objective is just power flow). It probably derives its name from the similarity between this solution method and the method used to solve a DC system, which is also linear, non-iterative and absolutely convergent. [17]

The approximated DC power flow equation is shown Eq. (A.1) [18]

\[ P_k = \sum_{j=1, j \neq k}^{N} B_{kj} (\theta_k - \theta_j) \]  

A.1

Where, \( P_k \) is the real power flow through the network. \( \theta_k, \theta_j \) are two voltage phasor angles at buses j and k. And \( B_{kj} \) is the imaginary part of the admittance matrix formula.

Given the total number of buses and lines, the topology of the network, and power flow injections at all buses except at the slack node bus, the power flow is possible to calculate, and an example for a 100 MW flow from point A to B through line C is shown in the following figure:

![Figure 54: Power flow from X to Y through Z](image)

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Appendices

Appendix B: Central storage model for the six regions

Figure 55 shows the RLDC for line 1 for the central storage. The storage maximum and minimum capacity requirements are less than the fictional large distance storage scenario.

Table 21 shows the capacity through lines 1 to 11 for the central storage model.

<table>
<thead>
<tr>
<th>Line</th>
<th>Repetition</th>
<th>Percentage eliminated</th>
<th>Capacity New max or min limit [MW]</th>
<th>Max</th>
<th>Min</th>
<th>% Max reduction of capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>0,51%</td>
<td>4560</td>
<td>6146</td>
<td>-1787</td>
<td>26%</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>0,26%</td>
<td>4177</td>
<td>4758</td>
<td>-1060</td>
<td>12%</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0,19%</td>
<td>1545</td>
<td>1818</td>
<td>-905</td>
<td>15%</td>
</tr>
<tr>
<td>4</td>
<td>44</td>
<td>0,50%</td>
<td>5819</td>
<td>6622</td>
<td>-1410</td>
<td>12%</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>0,59%</td>
<td>3056</td>
<td>3515</td>
<td>-1082</td>
<td>13%</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>0,41%</td>
<td>1988</td>
<td>2394</td>
<td>-1668</td>
<td>17%</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>0,17%</td>
<td>-2201</td>
<td>1237</td>
<td>-2583</td>
<td>15%</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>0,21%</td>
<td>-731</td>
<td>311</td>
<td>-847</td>
<td>14%</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>0,95%</td>
<td>-3391</td>
<td>1162</td>
<td>-3897</td>
<td>13%</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0,00%</td>
<td>0</td>
<td>754</td>
<td>-2789</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>32</td>
<td>0,37%</td>
<td>-4422</td>
<td>645</td>
<td>-4985</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 21: Line Parameters for the Central Storage Model
Appendices

Appendix C: Installed Wind and PV Capacity for Regions

Figure 56: Installed PV and Wind Capacity for All regions where Source is not Leading in Installed Capacity
Potenzial einer systematischen Standortwahl bei einem starken Ausbau der Kapazitäten von PV und Windkraftanlagen in Deutschland

Analyse des Speicher- und Transportbedarfs und eine Fallstudie für Marokko

Eine Masterarbeit im Rahmen des Studiengangs REMENA - eingereicht von Arabi Abdelhaq


Diese vorliegende MATLAB-basierte Studie analysiert das Potential einer systematisch-optimierten Standortwahl von Windturbinen und Photovoltaikanlagen (PV) in Deutschland, die die Residuallast und die verbleibenden Anforderungen an die zukünftige Energieversorgung minimiert. Zusätzlich wird eine vereinfachte Fallstudie für Marokko vorgestellt.

Die Studie untersucht die notwendige installierte Kapazität an Photovoltaik- und Windenergieanlagen, die aus der angewendeten Allokationsmethode resultiert und die Residuallast in Deutschland signifikant reduziert. Um die Auswirkungen einer optimierten Verteilung von Anlagen in kleineren Regionen auf das Gesamtsystem deutlich zu machen, wurde Deutschland in sechs Regionen unterteilt. Dies ermöglicht zudem die Betrachtung der benötigten Transport und Speicherkapazitäten, die den maximalen Lastanforderungen genügen.

Das in dieser Studie vorgeschlagene „sechs-Regionen-Szenario“ weist eine installierte Gesamtkapazität von 238 GW auf und reduziert die Residuallast um 69.18%. Dies stellt eine Verbesserung im Vergleich zu dem Szenario mit nur einer Region dar, welches eine Residuallast von 65% aufweist. Der durchschnittliche Lastfluss in den Gleichstrom-Übertragungsleitungen zwischen den Regionen beträgt 1.474 MW, welche primär für den Lastausgleich genutzt werden, bevor sekundär die Speicher im Bereich von 17 GW und 141.7 TWh Kapazität zum Einsatz kommen.

Die Resultate für die Speicherkapazität und den Transport werden mit zwei Szenarios verglichen: Deutschland als eine Region und einem zweiten Referenzszenario. Die Ergebnisse zeigen, dass die notwendige Transportkapazität um 27% und 12% und die Speicherkapazität um 13% und 2% geringer als in den beiden Vergleichsszenarios ist. Dies unterstreicht die Bedeutung der Nutzung eines regionalen Optimierungsansatzes, um den Bedarf an Speicher- und Übertragungskapazitäten zu reduzieren.

In der Fallstudie für Morocco wird die notwendige PV und Windenergiekapazität, die eine rein rechnerische Lastabdeckung garantiert, auf jeweils 19.520 MW und 12.250 MW geschätzt. Die Speicheroberforderungen wurden für beide Fälle untersucht und weisen klare Unterschiede auf: Im Fall der PV wird 27% weniger akkumulierte Speicherkapazität benötigt als bei der Nutzung von Windenergie.

Kassel, 28.02.12
الإمكانات المتاحة في توزيع مزيج ذي سعة عالية من مصادر الرياح و الطاقة الشمسية بطريقة منهجية في ألمانيا

تحليل متطلبات النقل والتخزين ودراسة حالة في المغرب

رسالة ماجستير مقدمة لبرنامج الطاقة الجديدة والمتجددة وكفاءة استخدام الطاقة - REMENA

تقديم: عربي عبد الحق

الملخص التنفيذي

واجه العالم تحديات جدًا تتعلق باستنزاف الموارد الطبيعية والنمو الاقتصادي المستمر و التزايد الدائم لعدد السكان مع أنماط حياة تستهلك الموارد بكفالة عظيمة. نتيجة لذلك، تعين على صناع القرار القيام بتحليل خيارات توزيع ودمج موارد الطاقة المتجددة المتاحة في ذلك للوصول إلى حلول ناجعة لهذه التحديات. البديل الأساسي هو توفير خيارات متعددة باستخدام الفعل للطاقة المتجددة في الحاضر والمستقبل قريب على حد سواء.

تقدم هذه الدراسة التكنولوجية من خلال استخدام برنامج MATLAB، بتحليل إمكانية توزيع منهجي و أمثل للتوربينات الرياح (wind turbines) والخلايا الشمسية (Photovoltaic panels) للحد من طلب الحمل على بنية توليد الطاقة في ألمانيا و تقدم حالة دراسة مبسطة في المغرب.

تستهدف هذه الدراسة تحليل نوع السعة المضافة (Installed capacity) للمطلوب للتأكد من إسهام الخلايا الشمسية وتوربينات الرياح في تلبية احتياجات استهلاك الطاقة في ألمانيا، و ذلك استنادًا إلى أساليب التوزيع المستخدمة في هذه الدراسة. بالإضافة إلى ذلك، تم تقسيم ألمانيا إلى ست مناطق لفحص الأثر المرتبط على تحسين توزيع الموارد في المناطق الصغيرة على النظام برمته، مما يسمح لنا أن نأخذ النقل ومتطلبات السعة التخزينية اللازمة لتحضير الحملة القطبية في الإعداد.

يقلل سيناريو "الأعمال الصغيرة" المقترح في هذه الدراسة بسعة إجمالية مضافة تبلغ 238,011 جيجاوات-الطاقة على الحمل بنسبة 69.18% و يؤدي بالتالي إلى تعطيلها بشكل أكبر في النطاق الصغير. بالإضافة إلى ذلك، بلغ المتوسط دفق الحمل لسعة خطوط النقل متوسط 1474 ميجاوات من خلال شبكة تيار مباشر (DC) بين المناطق الصغيرة لتحقيق توافر بين فائض و نقص انتاج الطاقة كل ساعة. قبل أن يتم في النهاية استخدام سعة تخزينية بمقدار 17,141 جيجاوات وسعة مركبة 141,737 تيراوات، مما يسهم علاج بعض الفروق بين النقص في الإنتاج والاستهلاك في كل ساعة وعلى مدار العام.

تمت مقارنة متطلبات السعة التخزينية وسعة النقل في سيناريوين آخرين: سيناريو ألمانيا كمنطقة واحدة وسيناريو مرجي أب، وأظهرت النتائج أن السعة التخزينية القصصية منخفضة في سيناريو المناطق الست بمقدار 27% عن سيناريو ألمانيا كمنطقة واحدة و12% عن السيناريو المرجي، كما أدى أن متطلبات السعة التخزينية لسيارات النقل والمزدح 13% عن سيناريو ألمانيا كمنطقة واحدة و2% عن السيناريو المرجي. ما يؤكد لنا فائدة استخدام سيناريو منطقية لتقليل متطلبات النقل والتخزين وحدد مناخ النظام. كل.

توفر دراسة الحالة في المغرب تقديرات نظرية للسعة المضافة المطلوبة لكل من الخلايا الشمسية وطاقة الرياح اللازمة لتحضير الحمل الكهربائي بشكل كامل، والتي وجد أنها تساوي 19520 ميجاوات و 12250 ميجاوات للخلايا الشمسية وطاقة الرياح على التوالي. تم أيضا دراسة متطلبات التخزين لكل حالات وتحليل الفروق بين خصائص التخزين هذا الحجم لكل مصدر حيث ظهر أن متطلبات السعة التخزينية للخلايا الشمسية أقل بنسبة 27% عن طاقة الرياح.

كاسل، ألمانيا

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