Using the concept of dynamic line rating to facilitate the integration of variable renewable energy and to optimize the expansion of the German power grid

Submitted by:

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List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
CIGRE	International Council on Large Electric Systems
DLR	Dynamic Line Rating
GDC	Generation Duration Curve
GVA	Gross Value Added
IEA	International Energy Agency
IEEE	Institut of Electrical and Electronics Engineers
LOPF	Linear Optimum Power Flows
MERRA	Modern-Era Retrospective analysis for Research and Applications
NTC	Net Transfer Capacity methodology
OSM	OpenStreetMap
PV	Photovoltaic
PyPSA	Python for Power System Analysis
RES	Renewable Energy System
SLP	Standard Load Profiles
SLR	Static Line Rating

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°C	Centigrade
°K	Kelvin
A	Ampere
EUR	Euro
GW	Gigawatt
km	Kilometer
kV	Kilovolt
kW	Kilowatt
m	Meter
mm	Millimeter
MW	Megawatt
MWh	Megawatt hour
MWt	Megawatt thermal
s	second
TW	Terawatt
TWh	Terawatt-hour
V	Volt

Acknowledgment

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There are always problems throughout every process to reach an important goal. In my case, I always have the support of my little brother. Thanks so much for being unconditional.

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Executive Summary

Global warming is one of the biggest issues that the world is facing (Quaschning and Eppel, 2020). Implementation and integration of renewable energies, such as wind and solar power, are called to change the high dependency on fossil fuels to supply energy necessities. This change represents significant adjustments in the generation and distribution paradigm because of the decentralization of generation and the inherent stochastic characteristics of wind and solar resources. Hence, the International Energy Agency (IEA) included dynamic line rating (DLR) as one of the tasks to cope partially with the integration challenge (International Energy Agency, 2021).

Nowadays, calculations on transmission lines capacities are based on the static line rating methodology (SLR). SLR uses the most unfavorable conditions to calculate power transmission constraints (Castel, 2015). It leads to underestimated values and low use factors in some cases. DLR is a more accurate estimation of a transmission line capacity that proposes to perform the calculations based on real-time ambient and conductor conditions (Zhan et al., 2017). Some potential benefits of using DLR are enabling additional network transmission capacity, facilitating the connection of generators based on renewables to the grid, and delaying network reinforcements.

The effects of applying DLR in a network with the complexity of the German power system to optimize the network expansion is of enormous interest. Therefore, this master thesis is focused on answering the following research questions:

- How should be developed the dynamic line rating analysis in a macro system like the German electric network?
- How much is increased the capacity of the overhead transmission lines due to DLR?
- What impacts did DLR have on the optimized network expansion in total system costs, network expansion requirements, and generation mix?

To solve these questions, first, an overview of the current development of DLR was performed in chapter 2. It was found out that the available studies about DLR are focused on its implementation on particular lines or small regions (Michiorri et al., 2015). There are not widely accepted researches about methodologies to evaluate the larch scale impact of DLR on planning country-level grids. In chapter 3, the selected method to calculate DLR and to analyze its effects is presented.

All the results are given in the form of a comparison with a no DLR simulation. The calculated DLR values are presented and interpreted in chapter 4, while chapters 5 and 6 introduce the scenario to perform the simulations and expose all the impacts of the additional transmission capacities on the future characteristics of the grid. Finally, the results are construed, and the author's conclusions are provided in chapters 7 and 8.

The major findings of this master thesis are:

- Even under conservative assumptions, the transmission capacity of the overhead transmission lines in Germany can be increased in an average range between 20 and 32%.
- The curtailment could be reduced for wind onshore, wind offshore, and solar PV from a total of 14.2 TWh to 1.2 TWh.
- The total amount of energy supplied by biomass generators, the most expensive technology in a scenario 100% based on renewable energy, can be reduced by 12% if DLR is used.
- A significant number of lines would not require any intervention, while the network reinforcement in other is considerably low compared with the simulation without DLR. The network expansion requirements can drop around 41.1%.
- Total annual marginal costs and total annual investment costs will decrease, leading to a decrement in the total yearly cost of the system of around 37.9%.

1 Introduction

Nowadays, energy has a central role in ensuring the quality of life of our society and guaranteeing the continued global economic development. Historically, a majority of the communities around the world rely heavily on oil, natural gas, and coal for their energy needs (Mohtasham, 2015). Global warming is a term that refers to the effect on the climate of human activities, such as burning the mentioned types of fossil fuels and large-scale deforestation, which cause emissions to the atmosphere of large amounts of greenhouse gases. Such gases take infrared radiation emitted by the Earth's surface, making it warmer than otherwise. Associated with this warming are climate changes such as more frequent heat waves, increases in rainfall, and increased frequency and intensity of extreme climate events (Houghton, 2005).

Because of its adverse impacts on human communities and ecosystems, global warming is the most critical environmental problem the world faces (Pielke et al., 2005). Adaptation to the unavoidable impacts and mitigation to reduce their scale are both necessary. International action is being taken by the scientific and political communities. Due to the need for urgent action, the greatest challenge is to hurry to increase energy efficiency and decrease fossil-fuel energy sources (Peters et al., 2013).

Due to mentioned environmental issues, a substitute source of energy had to be found. The solution to this is simple: renewable energies can completely cover all our energy supply needs within few decades (Quaschning and Eppel, 2020). Renewable energy technologies offer clean and abundant energy gathered from self-renewing resources such as the sun, wind, earth, and plants (Bull, 2001).

Narrowing down the problem to the German case, by 2020, 40.5% of the total energy consumed was produced through fossil fuels, while 43.8% comes from renewable sources. The last 15.7% was generated from other sources like nuclear and municipal waste (Statista, 2021). The German government aims to reduce greenhouse gas emissions by 40% under 1990 levels by 2020 and by 80-85% by 2050 from 1990 amounts. It implies that by 2050 this country will have a 100% renewable electricity supply (German

Advisory Council on the Environment, 2011). As can be expected, these changes represent multiple technical and social challenges that must be overcome.

Due to the stochastic nature of wind, clouds, and weather in general, the integration of wind power and photovoltaic generation into the power system poses complex challenges to the long-term planning of the transmission systems (Estanqueiro et al., 2018). Since wind and photovoltaics generation represents 23.7% and 9% of the total energy generation in Germany, respectively (Statista, 2021), and they are supposed to increase their participation and being the dominant energy sources over other renewables, finding options to integrate them in a technical and economically feasible way is one of the most important challenges in the coming years.

Transmission lines are a very scarce “product,” whereas the construction of supporting transmission and distribution networks is highly time and resource-consuming (Estanqueiro et al., 2018). Therefore, enabling more efficient utilization of transmission lines is an important issue that must be handled to integrate the new power generation plants. As a solution for that problem, the concept of Dynamic Line Rating can be used. It was proposed in 1960, but it was not technologically feasible to implement until in the late ’70s when the development and employment of SCADA and measurement sensor technology brought DLR closer to real-life applications (Sanna Uski-Joutsenvuo, 2012).

DLR has the potential to enable additional network transmission capacity, facilitate the connection of generators based on renewables to the grid, and delay network reinforcements. Furthermore, integrating DLR into power system operations may result in less greenhouse gas emissions, higher penetration of renewable energy, and increased social welfare in coupled electricity markets by lowering overall generation costs (Michiorri et al., 2015).

Historically, transmission and distribution networks are conservatively dimensioned, resulting in a typical usage rate lower than their maximum transmission capacity for security reasons. This is because the system is planned and operated to guarantee the highest possible security and supply quality, which involves using conservative worst-case assumptions at the planning stage, also known as static thermal rating (Castel, 2015).

DLR is a more accurate estimation of a transmission line capacity that proposes to perform the calculations based on real-time ambient and conductor conditions (Zhan et al., 2017).

The research question of this master thesis is to evaluate the impact of using DLR in the German transmission network in a future scenario. This analysis includes economic and technical aspects that can support the decision process about the convenience of implementing this concept or not. Additionally, since DLR was found feasible, a quantification of its impact on transmission capacity, system cost, generation mix, and network and storage expansion changes are presented.

2 Review of literature

One of the biggest challenges of variable renewable energies is their integration into the electric network due to the limited transmission lines capacity to transport energy, which leads to a curtailment in the generation and efficiency diminishment of the system. Based on this problem, the International Energy Agency created Task 25: Design and operation of energy systems with a large amount of energy generation (International Energy Agency, 2021). The most obvious way to overcome this obstacle is to build new lines to reinforce the network, but this solution is constrained by the high costs and legal difficulties of building them (Vinklers et al., 2016 - 2016). For this reason, the problem was approached from a different perspective, where the objective is to use more effectively the existing transmission and distribution network. That was how Dynamic Line Rating appeared as one of the most suitable options for this new approach.

DLR uses real-time, historical, and/or forecast weather data to calculate the instant capacity of transmission lines, enabling power system operations with higher thermal ratings than the ones specified by nominal conditions without compromising the physical operating limits of overhead lines (Estanqueiro et al., 2018). The physical operational limits that determine the capacity of a transmission line are the maximum conductor temperature and the clearance. Dynamic calculation of these parameters can be performed following the methodologies suggested by the Institut of Electrical and Electronics Engineers (IEEE) or the International Council on Large Electric Systems (CIGRE) (Castel, 2015).

Dynamic thermal balances of overhead power lines are proposed in the CIGRE Technical Brochure 601 and the IEEE Standard 738. The calculated temperatures are very similar between them, and according to multiple studies, the temperature error ($|T_{mesuared} – T_{calculated}|$) is less than 5°C 85% of the time (Arroyo et al., 2015). Therefore, CIGRE and IEEE standards are pretty reliable, provided that the weather data is accurate. But since it is not financially possible to install meteorological stations every 100m along the lines, it is crucial to decide where to get the weather data and how to use it in order to maximize the capacity, always guaranteeing safe operation.

Given the fundamental equations governing DLR, several studies propose methodologies to implement it, including enabling technology development, investment, DLR estimation, and decision-making approach (Erdinç et al., 2020). It makes sense to start by mentioning that DLR systems consist of communications and control technologies in an operations environment. These technologies include three components, which are sensors, communications devices, and software which are widely introduced by Akpolat et al., and Ntuli et al.

Fernandez et al. reviewed some technologies developed for real-time monitoring, as well as some case studies around the world, and presented the benefits and technical limitations of using DLR on overhead transmission lines. Its main focus was the advantages of DLR systems for wind integration.

Since numerous methods have been proposed for estimating the dynamic thermal capacity of overhead transmission lines, Black and Chisholm described and organized the key features of some of the main ones. Data from real DLR implementation provided a basis for assessing the variation in different parameters and characteristics of distributed measurement systems to be compared against point measurements systems.

Karimi et al. present a review with content similar to Fernandez et al. paper, which includes DLR objectives, field trial implementation, and monitoring technologies based on different strategies to determine the power line thermal capacity. But in addition, concerns and issues with implementing DLR as well as its practical difficulties are discussed. Also, future directions of DLR application are presented.

Probably the most technically exhaustive review on DLR is presented by Michiorri et al. Applied forecasting techniques for DLR were provided, and the impacts of each meteorological variable were analyzed separately. Also, evaluation of the available theoretical background and effectiveness of different forecasting techniques are complemented with economic aspects and limitations of DLR implementation.

Most of the academic papers are focused on methodologies, implementation, and economic evaluation of DLR or a mix of them, like the aforementioned studies. A. Douglass et al. went one step forward and analyzed the utility of forecasted DLR within the context of system operations. It includes aspects such as human and automation, operating philosophies, operating models, and software capabilities and processes.

Studies about DLR focus on its implementation on particular lines or small regions due to the complexity of the analysis and mainly because of the measurement equipment required (Michiorri et al., 2015). There are not widely accepted researches about methodologies to evaluate the larch scale impact of DLR on planning country-level grids.

Applying the DLR to systems like the German electric network, looking for network expansion optimization, demand a different methodology that should be carefully selected and implemented. The Principles for the Expansion Planning of the German Transmission Network (Tennet et al., 2020) propose a solution for the German study case.

3 Methodology

To answer the research questions, the activities were divided into two main stages. In the first stage, the dynamic capacities of the transmission lines in Germany are calculated for an entire year in hourly resolution. The procedure suggested in the Principles for the Expansion Planning of the German Transmission Network (Tennet et al., 2020) is used.

The document mentioned above is used for all the German transmission system operators (TSOs) to determine needs-based perspective network concepts for an efficient and safe network operation in the national and European legal framework and the obligations in the interconnected European operation. The first version of this document was released in 2012 when the TSOs presented technical and economic fundamentals of grid expansion planning in favor of the unity of grid optimization, grid reinforcement, and grid expansion to increase the necessary network expansion in the course of the energy transition (Amprion, 2021). Therefore, the methodology to calculate DLR proposed in the Principles for the Expansion Planning of the German Transmission Network was selected. It will be widely explained in the next section.

In the second stage, the economic and technical effects of considering the calculated DLR results are presented, based on comparing two different scenarios with and without DLR considerations.

3.1 Dynamic line rating calculation

The primary input to calculate the dynamic line rating for every overhead transmission line in Germany is accurate weather data. ERA-5 provides hourly estimations of a large number of atmospheric, land, and oceanic climate variables. The data cover the earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km (European Centre for Medium-Range Weather Forecasts, 2017). The available variables include temperature, wind speed, wind angle, and solar irradiation, which are the main variables required for DLR calculation according to the Cigré Technical Brochure 207 (Kanalik et al., 2019).

Due to the focus on planning the entire German system for future scenarios, methodologies suggested by the Institute of Electrical and Electronics Engineers or the

International Council on Large Electric Systems are unnecessarily complex because they were designed for detailed calculations of a particular transmission line. For this reason, using an appropriate simplification must be considered.

The Principles for the Expansion Planning of the German Transmission Network (Tennet et al., 2020) presents a simplified methodology to consider the impact of DLR in the planning of the energy system for future scenarios. There are two main assumptions that are the basis of the calculations:

3.1.1 Division of the German transmission network

Fraunhofer IEE carried out a study to further develop the methodology for determining the weather-dependent current carrying capacity of overhead lines in network expansion planning. Based on a mathematical clustering, it was proposed to divide the federal territory into nine regions (Th. Kanefendt, 2019). These regions can be observed in Figure 3-1.

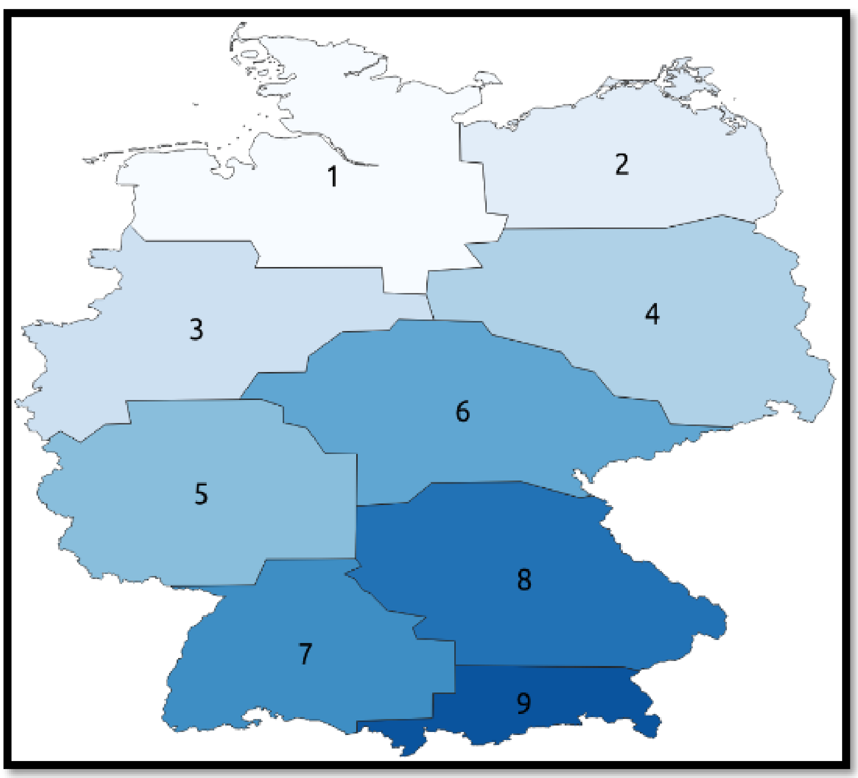

Figure 3-1: Representative regions in Germany for DLR analysis. Source: Author. Data from Th. Kanefendt, 2019

To establish these regions, a machine learning technic called K-Means was used. This method clusters samples based on similarities of its different characteristics. The used characteristics for this analysis were (Th. Kanefendt, 2019):

- The spatial distance
- The temporal relationship
- The difference between the mean continuous current load capacities between the individual grid fields.

The ultimate purpose of this division is to group all the overhead transmission lines of each region and assign the same DLR to all of them (in a percentage of its nominal capacity).

3.1.2 Hourly DLR calculation

Once the regions were defined, hourly DLR per each one of them must be calculated. The weather data from 2011 was used because, in terms of weather, the year 2011 can be regarded as a moderate wind feed-in and solar feed-in year in Germany (Tennet et al., 2020).

The DLR was calculated based on the “Investigation of the further development of the methodology for taking into account the weather-dependent overhead line load capacity in the expansion planning of the German transmission network” (Th. Kanefendt, 2019). The procedure to calculate the DLR follows the next steps:

- Find the lowest wind speed in each region in Figure 3-1. To perform this, for each region, the wind speed of every cell in the raster layer should be extracted and compared. This procedure will be repeated for each hour in the year 2011. The result will be 8760 lowest wind speeds per region.
- Find the highest temperature in each region in Figure 3-1. To perform this, for each region, the temperature of every cell in the raster layer should be extracted and compared. This procedure will be repeated for each hour in the year 2011. The result will be 8760 maximum temperatures per region.

- Use the previous values to find the maximum hourly capacity for each region based on Table 3-1. The values shown in this table were the result of a conservative study to determine safe operative conditions for DLR (Th. Kanefendt, 2019). These calculations use Equation 3-1, which is a steady-state thermal balance equation for conductors proposed in the CIGRE Technical Brochure 601, and the IEEE standard 738 (appendix DLR code, lines: 234 – 279).

$$q_c + q_r = q_s + q_j + q_m$$

Equation 3-1: Thermal balance equation for steady-state

Where:

q_c is the cooling due to convection,

q_r is the cooling due to the radiation to the surroundings,

q_s is the heating due to the solar radiation,

q_j is the heating due to the Joule effect,

q_m is the heating due to the magnetic effect.

Table 3-1: Criterium for DLR calculations. Source: Th. Kanefendt, 2019

Wind speed [m/s]	Assumed wind speed angle [deg]	Temperature [°C]	DLR [% of the nominal capacity]
< 3	90	< 35	100
< 3	90	< 25	110
< 3	90	< 15	120
< 3	90	< 5	130
> 3	30	< 35	105
> 3	30	< 25	115
> 3	30	< 15	125
> 3	30	< 5	135
> 4	30	< 35	110
> 4	30	< 25	120
> 4	30	< 15	135
> 4	30	< 5	145
> 5	30	< 35	115
> 5	30	< 25	130
> 5	30	< 15	145
> 5	30	< 5	150
> 6	30	< 35	125
> 6	30	< 25	140
> 6	30	< 15	150
> 6	30	< 5	150

3.2 Evaluate the impact of DLR on the future network requirements

The economic, technical, and social effects of implementing the previously calculated capacities will be studied in the second stage of the analysis. Network expansion requirements, annual costs, and other factors will be calculated and evaluated against the same scenario without using DLR. The software eTraGo and the scenario *eGo 100*, presented in detail in chapter 4, will be used.

eTrago is a Python package that stands for electric Transmission Grid optimization. It is part of the Open_eGo Project, which provides optimization strategies of flexibility options for transmission grids based on PyPSA (Python for Power System Analysis). Its main characteristic is that the German transmission grid is described by the 380, 220, and 110 kV voltage levels. It means that the distribution and transmission grid are part of eTraGo (Centre for Sustainable Energy Systems, 2021).

The main task performed by this program is to optimize the dispatch and capacities of generation and storage, as well as the transmission infrastructure. This operation is performed for a given number of hours (snapshots) in a year. The assumptions to run the optimization are as follows (PyPSA developers, 2021):

- It is assumed that the load is inelastic and must be met in every snapshot.
- The optimization uses continuous variables for most functionality; unit commitment with binary variables is also implemented for generators.
- The objective function is the total system cost for the snapshots optimized.
- Each snapshot can be given a weighting wt to represent, e.g., multiple hours.
- Each transmission asset has a capital cost.
- Each generation and storage asset has a capital cost and a marginal cost.

As it was mentioned, the objective function is the total system cost for the snapshot optimized. The complete formula is presented below to clarify how the objective function is conformed and which variables are being optimized.

$$Annual\ system\ cost = \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t * \left[\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t} h_{n,s,t}\right]$$

Where:

n: label the buses

t: label the snapshots

l: label the branches

s: label the different generators/storage types at each bus

w_t: weighting of time *t in the objective function*

$g_{n,s,t}$: dispatch of generator *s* at bus n at time *t*

$h_{n,s,t}$: dispatch of storage *s* at bus n at time *t*

$\bar{h}_{n,s}$: nominal power of storage *s* at bus *n*

$C_{n,s}$: capital cost of extending generator/storage nominal power by one MW

C_l: capital cost of extending the nominal transmission capacity by one MW

$o_{n,s,t}$: marginal cost of dispatch generator/storage for one MWh at time *t*

F_l: capacity of branch *l*

The annual system cost can be interpreted as the sum of three well-known components. The first term is the total capital cost of the new storage units necessary in the system. The second component is the total cost of the required network expansion. The last one is the sum of marginal costs of all the generators and storage units. Costs related to new generators are not considered since all the required to supply the demand are already created for the eGo 100.

4 Dynamic Line Rating calculations

In this chapter, the process of calculating DLR will be described. The procedure was divided into four main steps that will be explained in detail, including intermedium computations, which are important to fully understand the final findings. Additionally, the results of each step will be presented and analyzed. In the last part, the first mail results regarding DLR calculations are presented.

4.1 Ambient Temperature

The data provided by the European Centre for Medium-Range Weather Forecast (ERA-5) regarding temperature is given in Kelvin. To standardize units, all the values were converted into degrees Celsius using Equation 4-1.

$$T_{(°C)} = T_{(K)} - 273{,}15$$

Equation 4-1: conversion from Kelvin to Centigrade

Where:

$T_{(°C)}$: Temperature given in centigrade

$T_{(K)}$: Temperature given in Kelvin.

It was necessary to split the weather data into the nine regions presented in Figure 3-1 to start the calculations of the DLR. The weather data consists of 30 km side squares, where each square has only one unique value for each one of the variables (wind speed, temperature, etc.). It is important to mention that since the methodology includes finding the lowest wind speed and the highest temperature in each region (appendix DLR code, lines: 109 – 230), regions with bigger areas are more likely to find lower DLR values than could be expected. That could be the case of *Region 1,* which includes Schleswig-Holstein, where it is known that the average temperatures and wind speeds are especially favorable for high values of DLR.

In Figure 4-1 can be observed the monthly average maximum temperatures by regions. The values have the expected values due to seasonality. In general, the maximum differences are not greater than 4°C, where the highest temperatures are in regions 1, 3, and 5. On the other hand, regions 2, 8, and 9 present the lowest values. As it was already mentioned, the differences are not very significant. Thus, differences in DLR results will be mostly the result of differences in wind speed.

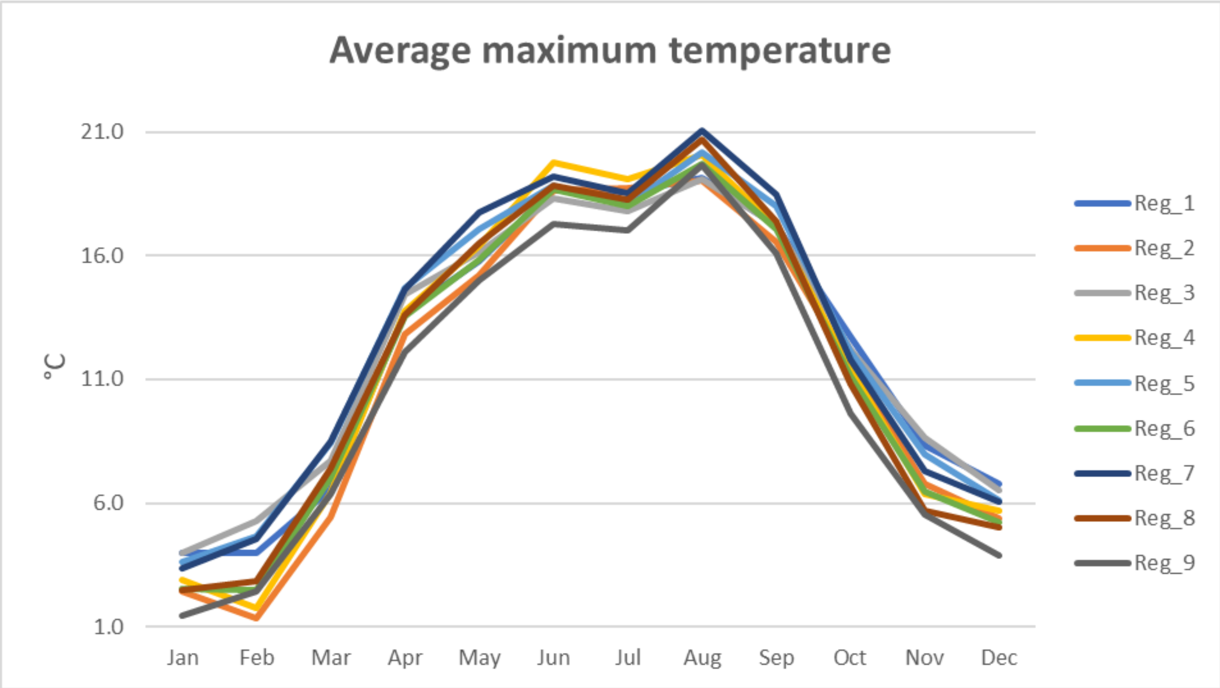

Figure 4-1: Average maximum temperatures per region for DLR calculation. Source: author. Data from European Centre for Medium-Range Weather Forecasts, 2017

4.2 Wind speed

ERA-5 provides hourly wind speeds at 10m over the ground level and the roughness factor Z_0 for every 30Km side square. For this analysis is required the wind speed at 50m, assuming that it is the average height of high voltage transmission lines in Germany. The transformation can be developed using the Logarithmic Law for wind (Kubik et al., 2011). The used equation can be seen in Equation 4-2. Calculation can be observed in appendix DLR code, lines: 109 – 230.

$$v = v_{ref} \cdot \frac{\ln \left({}^{Z}/_{Z_0} \right)}{\ln \left({}^{Z_{ref}}/_{Z_0} \right)}$$

Equation 4-2: logarithmic law for wind speed conversion based on altitude

Where:

v: wind speed to be calculated at height z

Z: height above ground level for wind speed v

v_{ref}: known wind speed at height z_{ref}

Z_{ref}: reference height where v_{ref} is known

Z_0: roughness length in the current wind direction

The average minimum wind speed can be observed in Figure 4-2. It is clear that there are significant differences between regions about this variable. Region 1 and 2 present the highest values throughout the entire year, reaching minimum average values of 6.8 m/s in December. Conversely, regions 7 and 9 have the lowest wind speeds with values between 1 and 2 m/s. It is important to highlight that in all the regions, the greatest values take place during winter, especially December, where the main peaks happen.

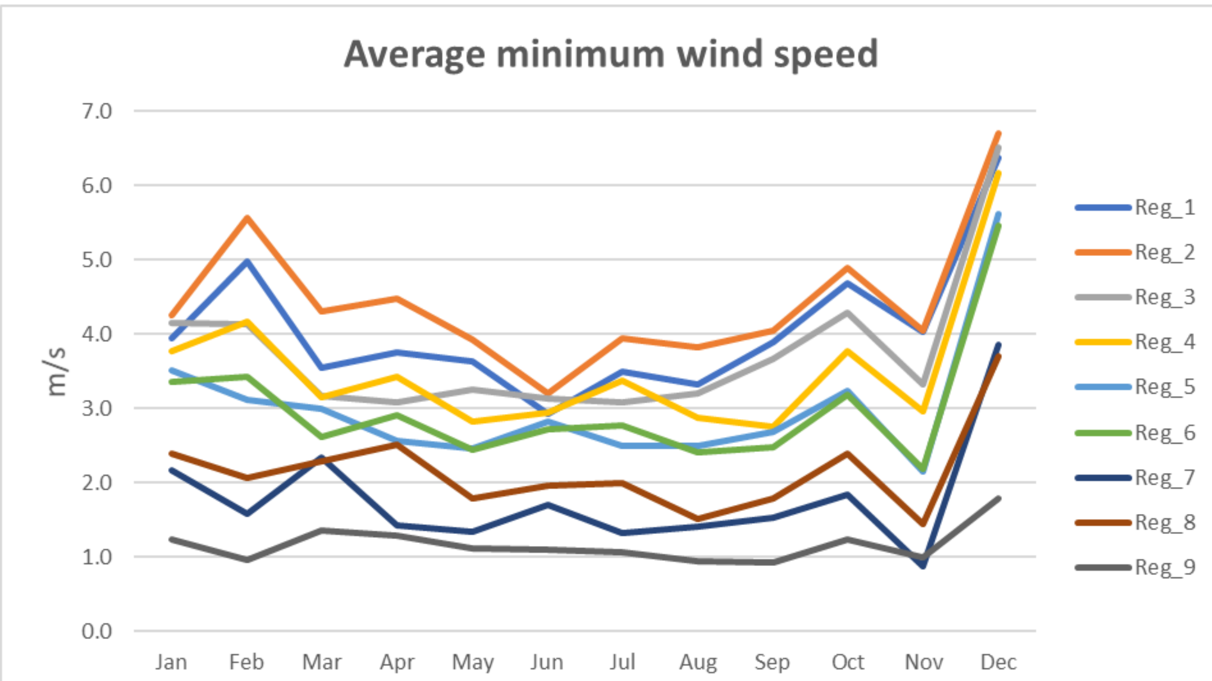

Figure 4-2: Average minimum wind speed per region for DLR calculation. Source: author. Data from European Centre for Medium-Range Weather Forecasts, 2017

4.3 DLR values per region

Once the hourly minimum wind speed and maximum temperature are calculated, DLR estimations can be performed. Hourly DLR per region is calculated for an entire representative year using Table 3-1. Since the temperature in the different regions shows no substantial differences, regions with the highest wind speeds were supposed to have the biggest DLR values. Final average DLR values per region and month can be observed in Figure 4-3. Regions 1 and 2 have the best conditions to allow extra transmission power capacity, reaching in December capacities in an average of 147% of the nominal capacity of the transmission lines inside them.

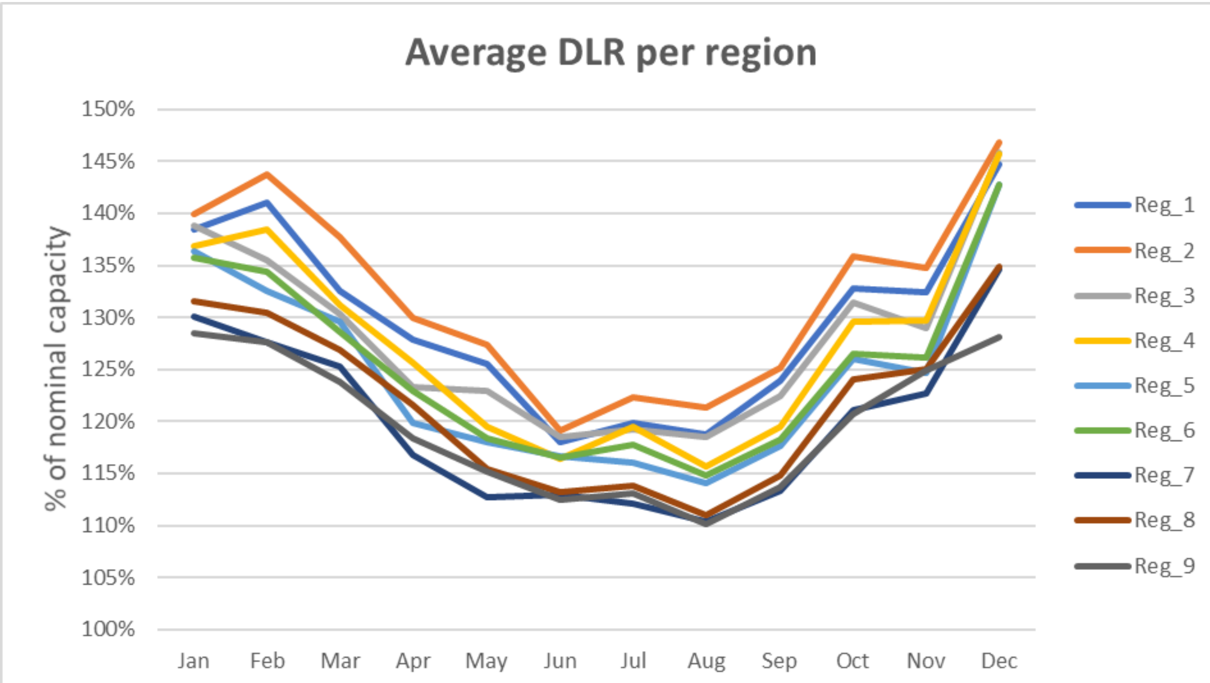

Figure 4-3: Average DLR per region for 2011. Source: author

On the other hand, in regions 7 and 9, the DLR values are the lowest in the country. On average, they are in the range of 110% to 130% throughout the year. This still represents an important increment of power capacity even in the least convenient areas. It can be identified that even though wind speed determines in which regions the DLR values are higher, the temperature defines the seasonal behavior. More detailed information about DLR values per region can be found in appendix 11.1: Histograms for DLR per region.

4.4 Associate transmission line to the regions

Once hourly DLR values per region were calculated, they must be assigned to the transmission lines inside their areas. Data about medium voltage and high voltage transmission lines were retrieved from Open Street Map (OpenStreetMap contributors, 2015). To assign the DLR values, it was found that there are four different cases:

- Underground transmission lines: The DLR concept is only applicable to overhead transmission lines since ambient temperature, wind, and other climatic factors do not affect their operation conditions. For this reason, the transmission capacity of all the underground lines is not affected. It means that the capacity of these lines will be 100% of the nominal capacity throughout the whole year (appendix DLR code, lines: 69 – 73).

- Transmission lines out of the borders: For this study, lines interconnecting the German electrical network with other countries were considered to have a constant capacity factor of 100% of the nominal capacity throughout the whole year (appendix DLR code, lines: 64 – 67).

- Transmission lines completely into one region: When a line belongs only to one of the nine regions, the hourly DLR of the region is assigned to the line (appendix DLR code, lines: 76 – 80).

- Transmission lines in two or more regions: When a line intersects more than one region, the lowest DLR value between those regions is found for each hour of the year of analysis. Then the collection of lowest values is assigned to the line (appendix DLR code, lines: 83 – 88).

All the calculations described in the methodology and this chapter were implemented using the programming language Python and the libraries Pandas, Geopandas and Numpy, among others. The mentioned code can be found in appendix 11.2: DLR calculation code.

The final distribution of the transmission lines in the different regions can be observed in Figure 4-4. In this figure, it is possible to visualize that most of the transmission lines are located in the south of the country, where the calculated DLR values are low in comparison with the rest of the country.

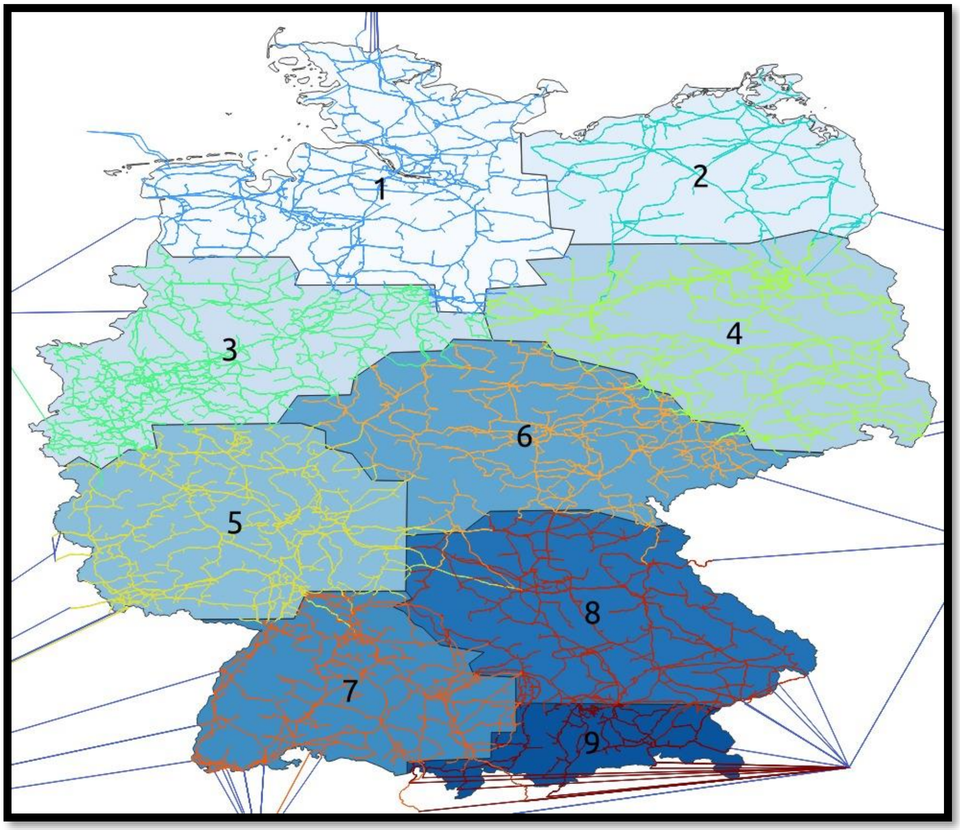

Figure 4-4: Transmission lines division by regions. Source: Author. Data from Open Energy Community, 2021

The result of dividing and grouping the transmission lines can be seen in Table 4-1. A total of 19.167 transmission lines with a total length of 107.082 Km were considered for this study. There are 71 lines grouped in *Region 0.* They are interconnections to other countries, and their capacities are not affected. Moreover, the 864 underground lines are affected neither.

In the end, only 18.303 transmission lines will be affected by the dynamic line rating calculations. Region 3, with 5252, has the highest number of transmission lines and total kilometers. Contrarily, region 9 has the smallest amount with only 400 lines. Regarding the region with the best DLR values, Region 2, there are only 830 lines inside it. To evaluate the impact of the implementation of DLR, the next section will present a comparison between two different scenarios to quantify the effect of DLR in terms of economic and technical aspects. For a better understanding of the described results, in chapter 11.1 can be found the histograms for each region.

Table 4-1: Distribution of transmission lines per region. Source: author

Region	Underground transmission lines		Overhead transmission lines	
	Number	Length [Km]	Number	Length [Km]
0	0	0.0	71	16279.6
1	135	473.6	2534	12480.9
2	27	81.2	830	5993.4
3	141	287.6	5252	17030.4
4	270	469.2	1988	11129.4
5	64	109.7	2607	12703.3
6	38	66.7	1655	8814.8
7	68	136.6	1711	9004.1
8	47	149.7	1255	7228.7
9	74	525.7	400	4117.9
Total	**864**	**2300.0**	**18303**	**104782.3**

5 Scenario definition and simulation parameters

5.1 The eGo 100 scenario

The scenario that will be used to quantify the potential effects that dynamic line rating could have on the expansion of the German power grid was developed by eGo^n. It is a project financed by the Federal Ministry for Economic Affairs and Energy, which aims to investigate the effects of sector coupling on the electrical grid and the benefits of new flexibility options (eGosupn/sup, 2020). Along with the development of the project, multiple tools and scenarios were created to deal with the effects of the expansion of renewable generation capacity and the progressing electrification of other energy sectors.

The base scenario used for this work is called *eGo 100*. Its main characteristic is the absence of fossil fuels for energy purposes. Therefore this electrical energy system must be powered 100% from RE (Mueller et al., 2018). It is mainly based on the *100% RES scenario of the e-Highway2050 - Modular Development Plan of the Pan-European Transmission System 2050 (e-Highway2050, 2021).* The Scenario specifications can be seen in Table 5-1 and Table 5-2.

Table 5-1: specifications scenario eGo 100. Source: Müller et al., 2019

Characteristic	Scenario eGo 100
Share of RES in installed capacity	100%
Net electricity consumption (TWh)	506.0
Annual peak load (GW)	87.01
Share of renewable energy in el. Consumption	100%

Two columns can be observed in Table 5-2 for generation capacities: Germany and Entire model. The first one includes the expected installed capacity in Germany for this scenario. The second column has the entire installed capacity per technology for the whole analyzed system. It must be done in this way since the interaction between the German power grid, and the neighbor networks is of high relevance to calculate Linear Optimum Power Flows (LOPF).

Table 5-2: Generation capacities scenario eGo 100. Source: Müller et al., 2019

Generation capacities in GW	eGo 100	
	Germany	Entire model
Nuclear energy	0.0	0.0
Lignite	0.0	0.0
Hard coal	0.0	0.0
Natural gas	0.0	28.5
Oil	0.0	0.0
Waste materials	0.0	0.0
Other conv. Generation	0.0	0.0
Sum conv. Production	**0.0**	**28.5**
Onshore wind	98.4	382.1
Offshore wind	27.0	65.9
Photovoltaics	97.8	300.1
Biomass	27.8	93.3
Hydropower	3.2	84.5
Sum renewable generation	**254.2**	**925.9**
Total	**254.2**	**954.4**

The eGo 100 scenario has a high spatial resolution regarding all the electrical components such as substations and transmission lines, which is a fundamental condition to perform the calculations about the impact of DLR. Although developing a data set built on publicly available sources including all voltage levels is challenging, an open-source approach was possible thanks to data from governmental authorities and the public database OpenStreetMap (OSM) (Hülk et al., 2017).

Next, it will be briefly described the methods and data sources that were applied to create the used grid model. The first group formed by allocation of substations, demand, and generation, will be a summary of the document Allocation of Annual Electricity Consumption and Power Generation Capacities Across Multiple Voltage Levels in a High Spatial Resolution (Hülk et al., 2017). The second group contains the generation of time series data for load, wind power output, and solar power output.

- Substations: Data from OSM was used as the main input to identify relevant substations. Due to the no homogeneous data quality in OSM, it was necessary to filter the obtained available information. The used filters can be found below:

a. Voltage ≥ 60,000 V or line starts/ends at a substation

b. Situated within the administrative boundary

c. Frequency ≠ 16.7 or 16.67

d. Operator ≠ DB_Energie or DB Energie GmbH or DB Netz or DB Netz AG

e. Substation ≠ transition or traction (aggregate substations that are situated within a distance of 75 m from their boundary)

- Demand: The methodology for a spatial allocation of demand varies according to each sector. The annual households electricity consumption is distributed based on the allocation of population, assuming a direct correlation between the electricity consumption in the reference area and the number of inhabitants. The distributions of the annual electricity consumption generated for the scenario eGo 100 can be observed in Figure 5-1.

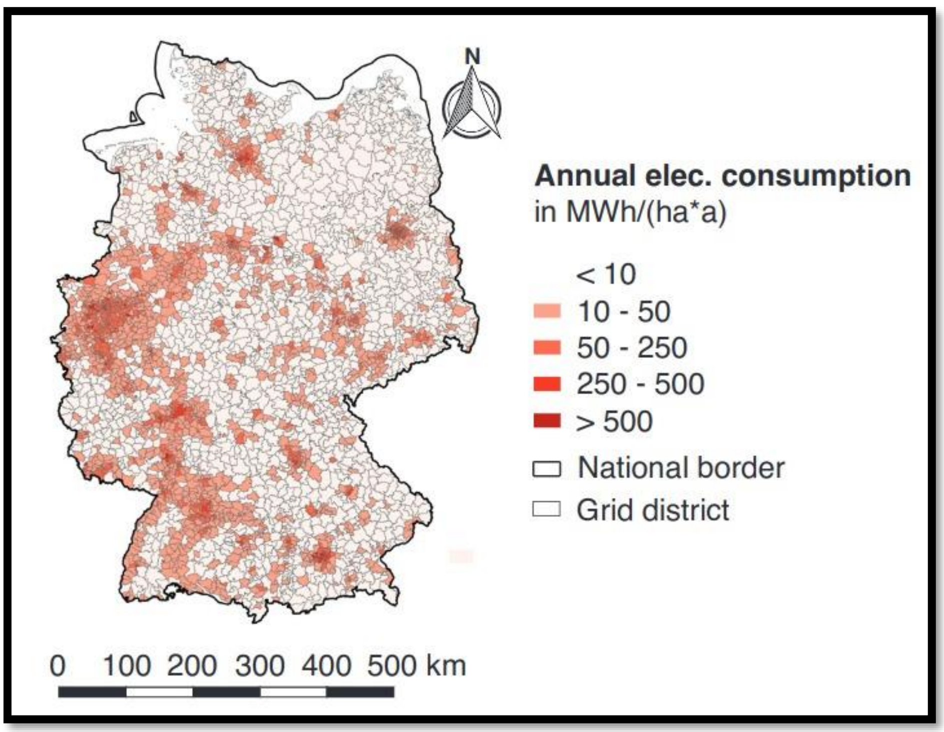

Figure 5-1: Annual electricity consumption for the scenario eGo 100. Source: Hülk et al., 2017

For the industrial and retail sectors, a relationship between electricity consumption and gross value added (GVA) is supposed. The annual industrial and retail sectors' consumption is broken down to the level of administrative districts using the GVA.

- Generation: Active power generators are extracted from official and publicly available data bases such as the power plant registry published by the German Federal Network Agency (Bundesnetzagentur) (Bundesnetzagentur - kraftwerksliste-node, 2021) and a renewable energy system (RES) registry published by a solar industry trade group.

  Generators with a voltage levels of 110 kV or lower are designated to transition points with voltage tags of 110 kV by doing a spatial comparison between the generator site and the medium voltage grid districts. The generators with voltage levels over 110 kV are assigned to the transmission substations employing the high voltage grid districts.

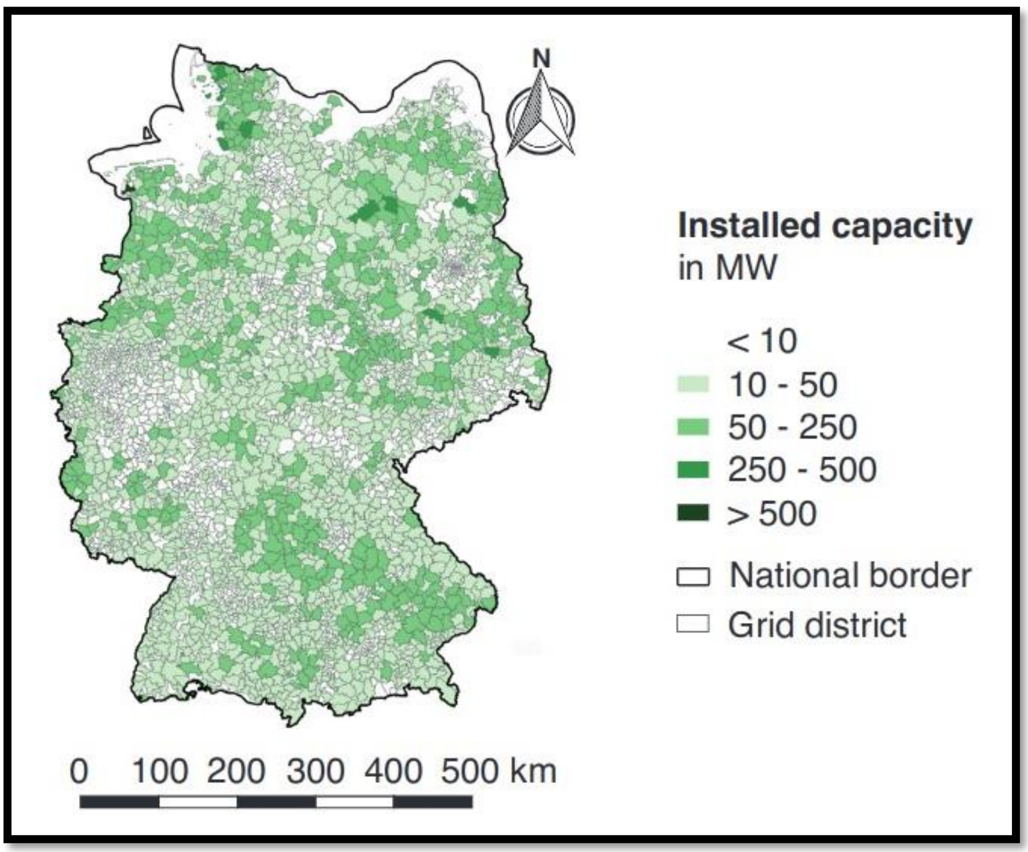

Figure 5-2: installed capacity for the scenario eGo 100. Source: Hülk et al., 2017

- Load time series: to obtain a consistent set of demand data valid across low-voltage grid levels in Germany, standard load profiles (SLP) (Hayn et al., 2014) were used. SLP has the electricity demand characteristics of the residential, retail, and agricultural sectors at a temporal resolution of 15-minutes. A pattern for electricity demand of the industrial sector was constructed based on a stairs function (Mueller et al., 2018). The industrial demand pattern considers peak and off-peak times. During a workweek at day-time (6 a.m. to 10 p.m.), the normalized load curve adds up to 0.8. At other times this parameter was set to 0.6. Spatially highly resolved and sectorally disaggregated annual consumption calculations can be studied deeper in the document The eGo grid model: An open-source approach towards a model of German high and extra-high voltage power grids (Mueller et al., 2018).

- Solar power output time series: There are multiple high-quality time series data profitable providers used by project developers interested in confirming possible solar sites. It includes 3TIER1 and Geomodel Solar2, which can cost thousands of euros for one single location. Therefore, since eGo^n is done for academic purposes, it was necessary to find a free source solution that achieves the accuracy required levels.

  The proposed solution was to use Meteorological reanalyzes. They have appeared as a valuable data source for renewable energy modeling. Some of its advantages are that reanalysis data are usually available globally and they provide several decades of coverage. Additionally, they are usually freely available (Pfenninger and Staffell, 2016).

  In particular, to calculate the solar power output time series for the scenario ego 100, the reanalysis was performed by the Modern-Era Retrospective analysis for Research and Applications (MERRA), designed by NASA (MERRA, 2021).

Since the optimization formula is focused on minimizing the annual system costs, it is important to present the values that were used to run all the calculations presented in this document. In Table 5-3, Table 5-4, and Table 5-5 can be found all the relevant investment and marginal costs used to calculate the final results.

Table 5-3: Marginal costs according to the energy source for scenario eGo 100. Source: Müller et al., 2019

Energy carrier	Marginal cost [EUR/MWh]
Natural gas	56.05
CHP <10 MW	31.63
Biomass	31.63

Table 5-4: Exogenous assumptions on grid expansion costs in the extra high voltage and high voltage level for the scenario eGo 100. Source: Müller et al., 2019

Component	Investment costs		Marginal costs	
	Million EUR	per	EUR	per
AC line, 380 kV	0.2	km	85	MVA * km
AC line, 220 kV	0.15	km	290	MVA * km
AC line, 110 kV	0.06	km	230	MVA * km
Transformer, 380-220 kV	8.5	Unit	14167	MVA
Transformer, 380-110 kV	5.2	Unit	17333	MVA
Transformer, 220-110 kV		Unit	7500	MVA
DC line	1.5	km	375	MW * km
DC converter	0.2	Unit	200,000	MW

Table 5-5: Exogenous assumptions about storage expansion and operating costs for the scenario eGo 100. Source: Müller et al., 2019

	Batteries Li-Ion	Hydrogen storage
Investment costs Power (EUR / MW)	45	575
Investment costs Energy (EUR / MWh)	106	0.5
Investment costs in total (EUR / MW)	678	651
Operating cost (KEUR / MW / a)	0.44	1.62

5.2 Simulations parameters

The main objective of this work is to find the technical and economic impact of applying the DLR concept in the network expansion of the German power grid. As was mentioned above, the software eTraGo (Centre for Sustainable Energy Systems, 2021) is used for this purpose. Next, it will be introduced the main parameters that were used to calculate the results presented in the coming subsections of this chapter.

- Database: The topology and all the data regarding the current status of the German power grid are available for free use on the Open Energy Platform website (Open Energy Community, 2021). It is one of the tools developed by the Open Energy community that aims to ensure quality, transparency, and reproducibility in energy system research. Since it is a collaborative community effort, everything is openly developed and therefore constantly evolving.

- Scenario: as was mentioned in the previous chapter, the scenario eGo 100 will be used.

- n_clusters: since it is computationally extremely high demanding to perform an analysis with all the lines and busses that form the German power grid, the complexity of the network is reduced by using the k-mean technic. The parameter n_cluster sets the number of nodes that the new network will have. For this simulation, 300 nodes were selected based on the good performance/complexity balance experimented with in previous studies (Mueller et al., 2018). The resulting network can be observed in Figure 5-3 and is used for the case study with and without DLR to make the results comparable. The transmission lines connecting to the neighboring countries (Denmark, Poland, Netherland, France, Switzerland, Austria, Czechia, and Sweden) are considered as part of the network, but no DLR values are calculated for them according to the description in chapter 2. For this reason, the next plots will be center on the transmission lines inside Germany.

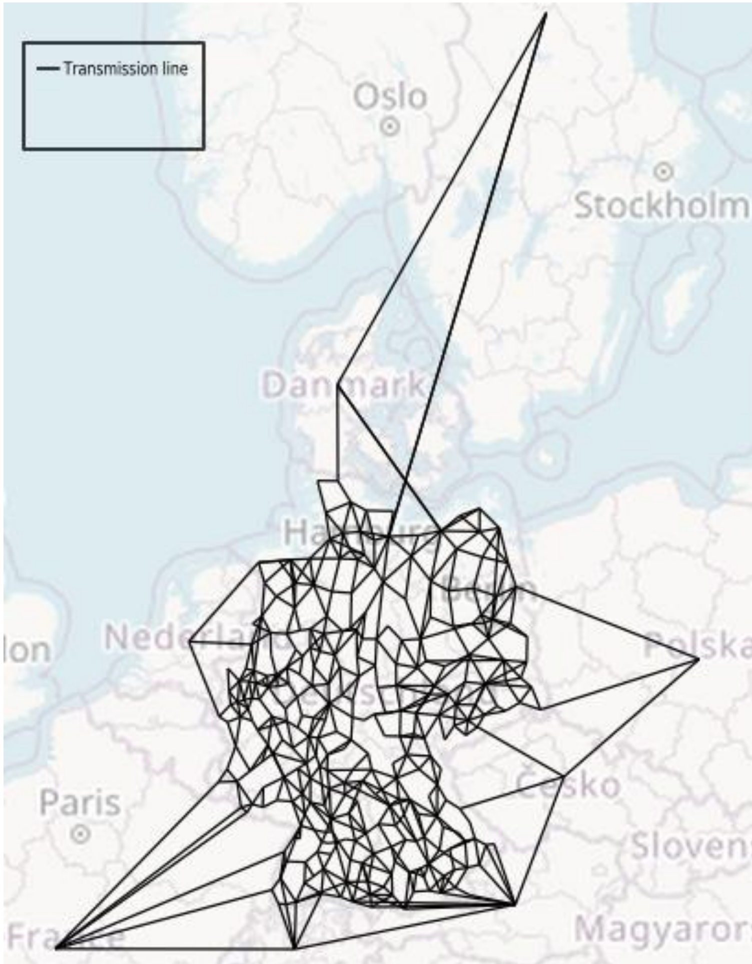

Figure 5-3: German power grid represented by a 300 nodes network. Source: author

- Start and end snapshot: the analysis is performed hourly for one entire year. Therefore, the analysis will be limited to the first hour until the last hour of 2011. Due to the extremely high computational resources that 8760 LOPF would require, some hours are skipped according to the parameter "skip snapshots."

- Skip snapshots: This parameter received an integer as input. For this calculation, this parameter was selected as five based on previous studies carried out using eTrago. It means that a LOPF will be performed for 1 of each 5 hours of the analysis. The values of the next 4 hours are the same as in the last calculated snapshot.

6 Results: impact of dynamic line rating

Throughout this paragraph, all the technical and economic findings calculated with eTraGo will be presented. In general, the results will be shown in the form of a comparison between the business as usual scenario (No DLR) and the scenario using the DLR concept. An extensive analysis of these results can be found in the chapter: Discussion.

6.1 Network expansion

The 300 nodes network (Figure 6-1) is used to evaluate the potential impact of DLR on the grid expansion. No additional transmission line will be considered. The network expansion is the result of increasing the transmission capacity of the existing transmission lines. A first impression about the impact of DLR can be built based on Figure 6-1. In this figure is possible to realize that the number of transmission lines that require to increase their capacity in the calculation without DLR is significantly higher than the ones with DLR.

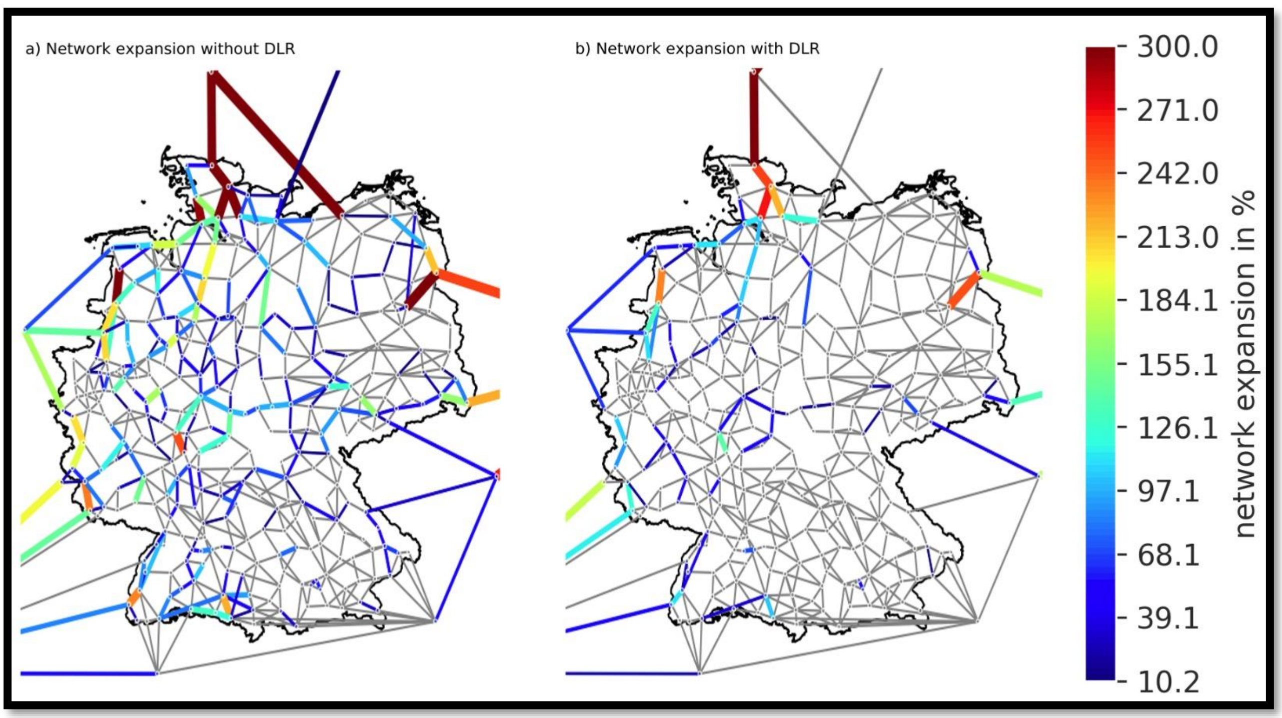

Figure 6-1: Required network expansion in absolute values for scenario eGo 100. a) without DLR. b) with DLR. Source: author

Moreover, the lines that need transmission expansion in the scenario with DLR require significantly less than the ones in the no DLR Scenario. It can be observed in Figure 6-2 the potential difference in percentage that using DLR could have in the grid expansion process. The scale bar starts at -6.44%, which is the result of the interconnection between Germany – Denmark, which was not considered to change its capacity in this analysis, as well as all the other interconnections. The values for network expansion difference shown in Figure 6-2 are calculated individually per transmission line using Equation 6-1

$$Ne_{diff} = \frac{Ne_{No\ dlr} - Ne_{dlr}}{Ne_{No\ dlr}}$$

Equation 6-1: network expansion difference

Where:

Ne_{diff}: Network expansion difference

$Ne_{No\ dlr}$: Network expansion No DLR scenario

Ne_{dlr}: Network expansion DLR scenario

The biggest differences correspond to values even higher than 60% and are mostly located in the very north of the country, where it was found that DLR values are on average higher than in other regions in Germany.

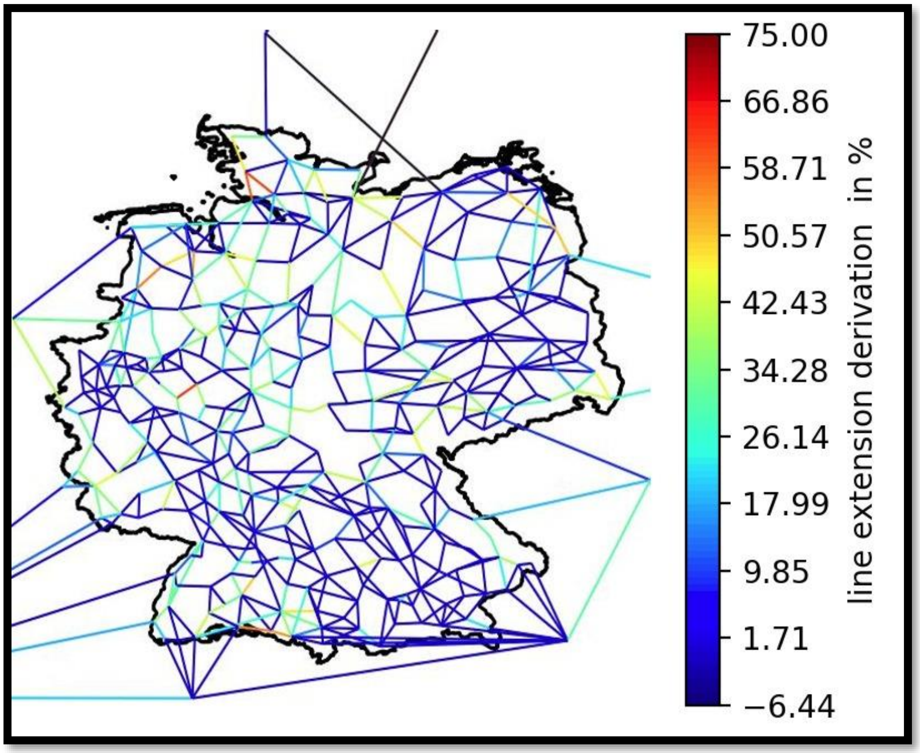

Figure 6-2: Network expansion difference between the scenarios with and without DLR. Source: author

The simplified network shown in Figure 5-3 has in total 679 transmission lines. The calculations without considering DLR suggest that 232 of those will require an extension to work under the conditions determined for the eGo 100 Scenario. On the other hand, if DLR is taken into account, 75 transmission lines will need intervention. In Figure 6-3 it can be easily quantified the comparison. It is important to mention that every line that does not require extension is one less legal and social process to hold, which means savings in terms of time and money. Economic impacts will be analyzed in the third section of this chapter.

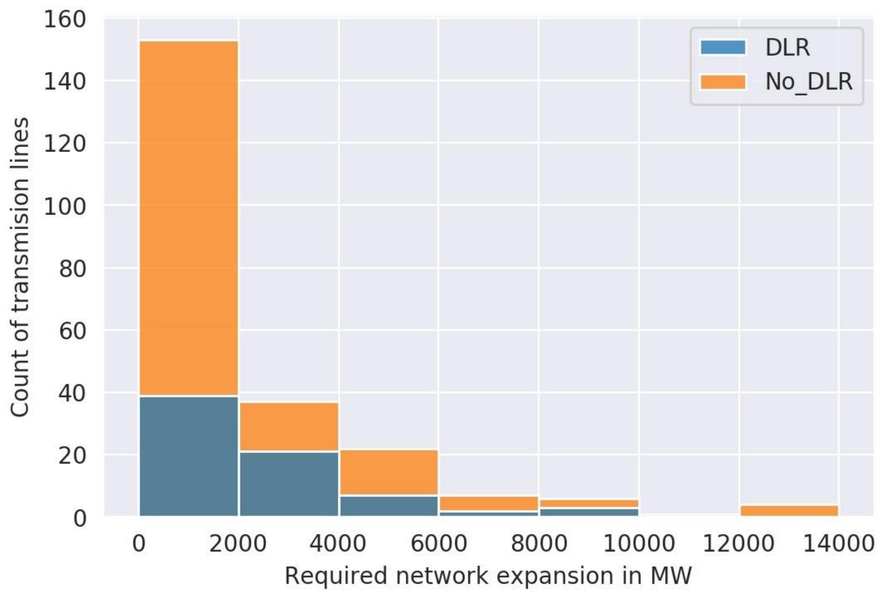

Figure 6-3: Histogram network expansion requirements with and without DLR. Source: author

In order to quantify the reduction in network expansion, an indicator that considers the expansion and length of each transmission line in both scenarios must be used. This calculation can be seen in chapter 7.

6.2 Curtailment

To analyze the impact of DLR in terms of curtailment in the eGo 100 scenario, three different comparisons between the amount of curtailed energy vs. dispatched energy will be presented. These figures are designed in the form of generation duration curves, which are largely utilized to illustrate the connection between generation capacity requirements and capacity utilization (Poulin et al., 2008). A generation duration curve (GDC) is similar to a generation curve, but the generation data is ordered in ascending order of magnitude rather than chronologically. The height of each segment is a measure of capacity, and the width of each segment is the utilization rate or capacity factor. The product of the two above mentioned is a measure of electrical energy, in this case, MWh.

Since solar irradiation and wind are the only energy sources included as carriers in the scenario that can be only partially predicted but no controlled in terms of availability, the results will focus on wind onshore, wind offshore, and solar PV.

The first result that will be presented is the wind onshore curtailment. The eGo 100 scenario has a total installed capacity of 382.1 GW for this technology, of which 98.4 GW are in the German territory (Mueller et al., 2018). The curtailment showed in this analysis corresponds only to generators connected to busses inside Germany. In Figure 6-4 can be seen the behavior of the energy dispatched and the energy curtailed during an entire year. In the scenario without DLR, there is a potential to produce about 160.2 TWh per year, but more than 3.1 TWh are curtailed. It means that 1.9% of the energy is not produced because of network limitations.

In the scenario with DLR, the curtailed energy decreases to 0.81 TWh. It indicates a curtailment of 0.5%, which represents a **reduction of 73.6%** in the curtailed energy.

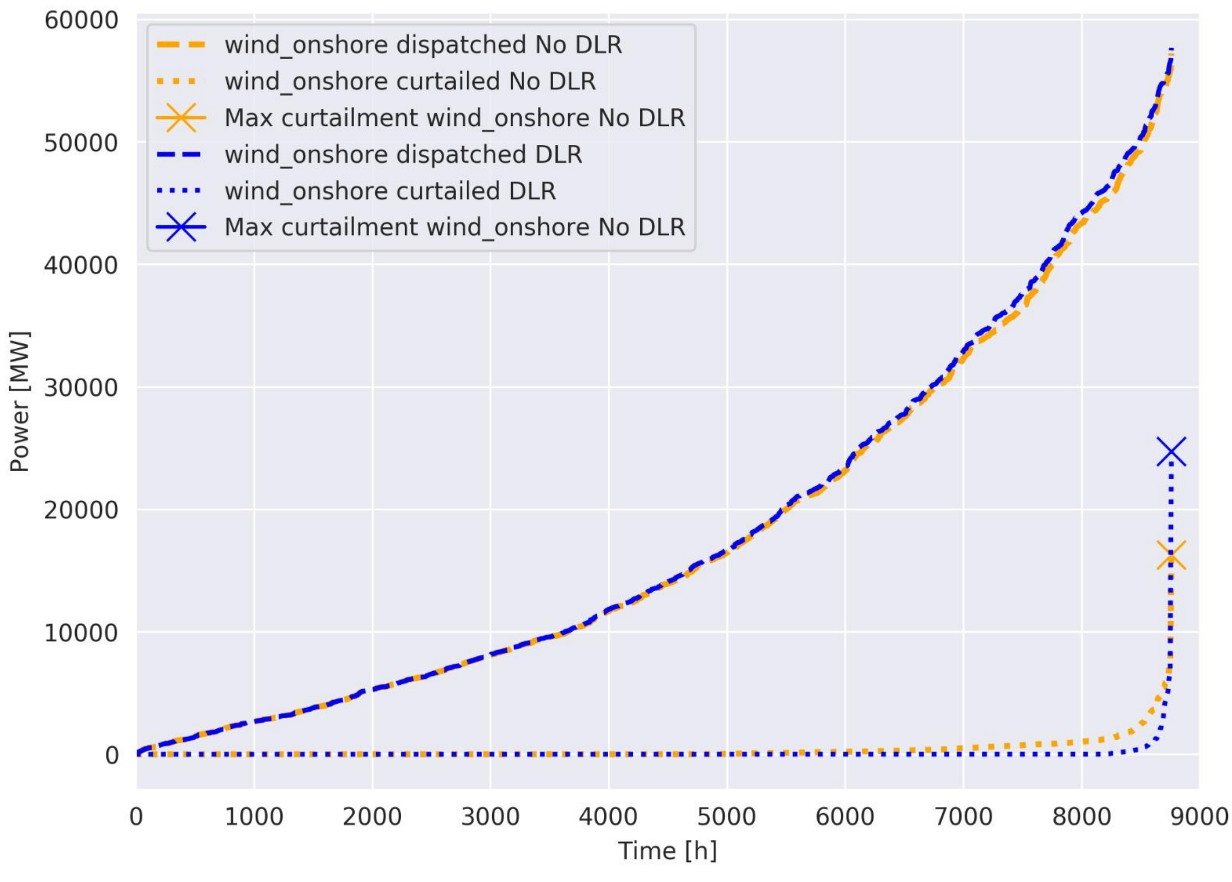

Figure 6-4: Yearly wind onshore duration curve for 2011. Source: author

Regarding offshore wind curtailment, the used scenario has a total installed capacity of 65.9 GW for this technology, of which 27.0 GW are in the German territory (Mueller et al., 2018). In Figure 6-5 can be observed how the energy dispatched, and the energy curtailed fluctuate. The calculations without DLR show a potential to produce about 103.0 TWh per year, but more than 10.3 TWh are curtailed. It means that 10.0% of the energy is not produced because of network limitations.

In the scenario with DLR, the curtailed energy decreases to 0.15 TWh, which indicates a curtailment of 0.1%.

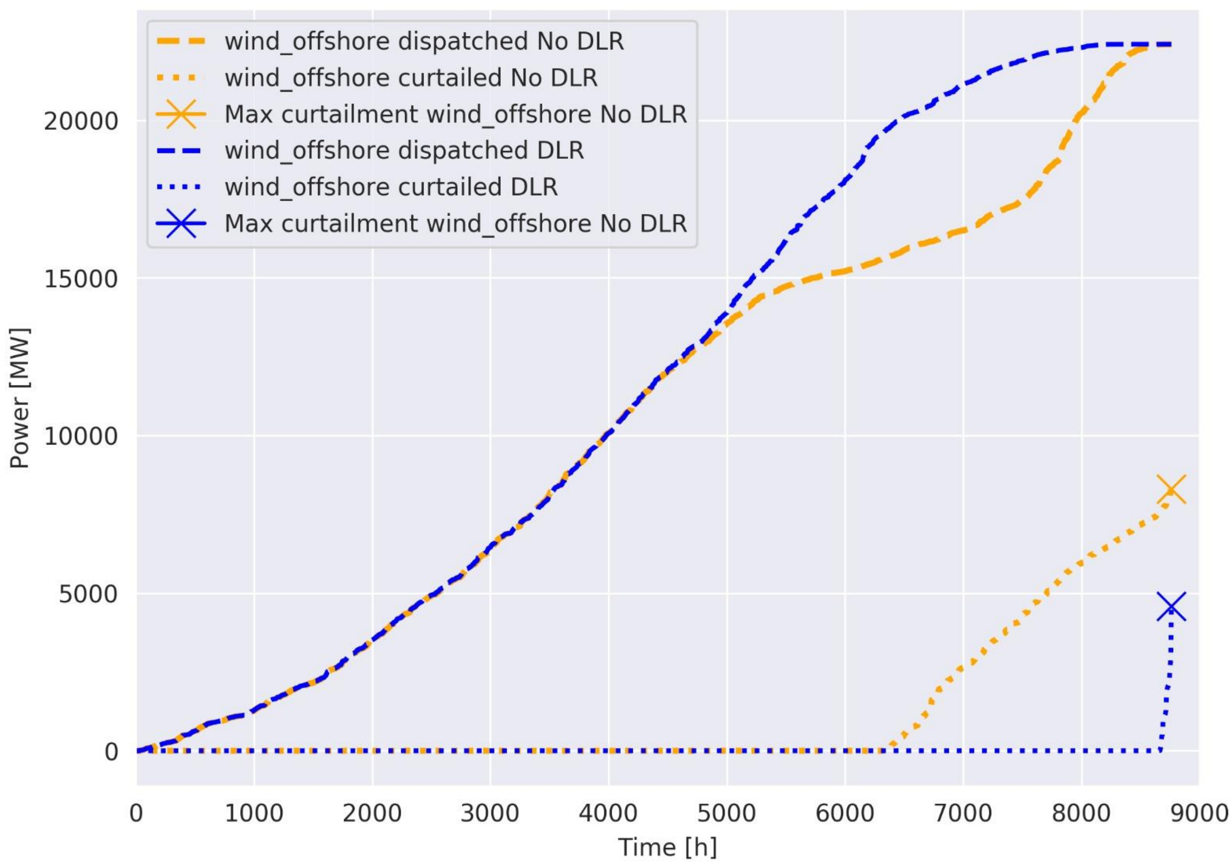

Figure 6-5: Yearly wind offshore duration curve for 2011. Source: author

Finally, results in terms of curtailment for solar PV are presented. The eGo 100 scenario has a total installed capacity of 300.1 GW for solar PV, of which 97.8 GW are located in Germany (Mueller et al., 2018). In Figure 6-6 can be seen the behavior of the energy dispatched and the energy curtailed during the year of analysis. In the scenario without DLR, there is a potential to produce about 94.7 TWh per year, but more than 0.7 TWh are curtailed. It means that 0.7% of the energy is not produced because of network limitations.

In the scenario with DLR, the curtailed energy decreases to 0.22 TWh. It indicates a curtailment of 0.2%, which represents a **decrement of 68.5%** in the curtailed energy.

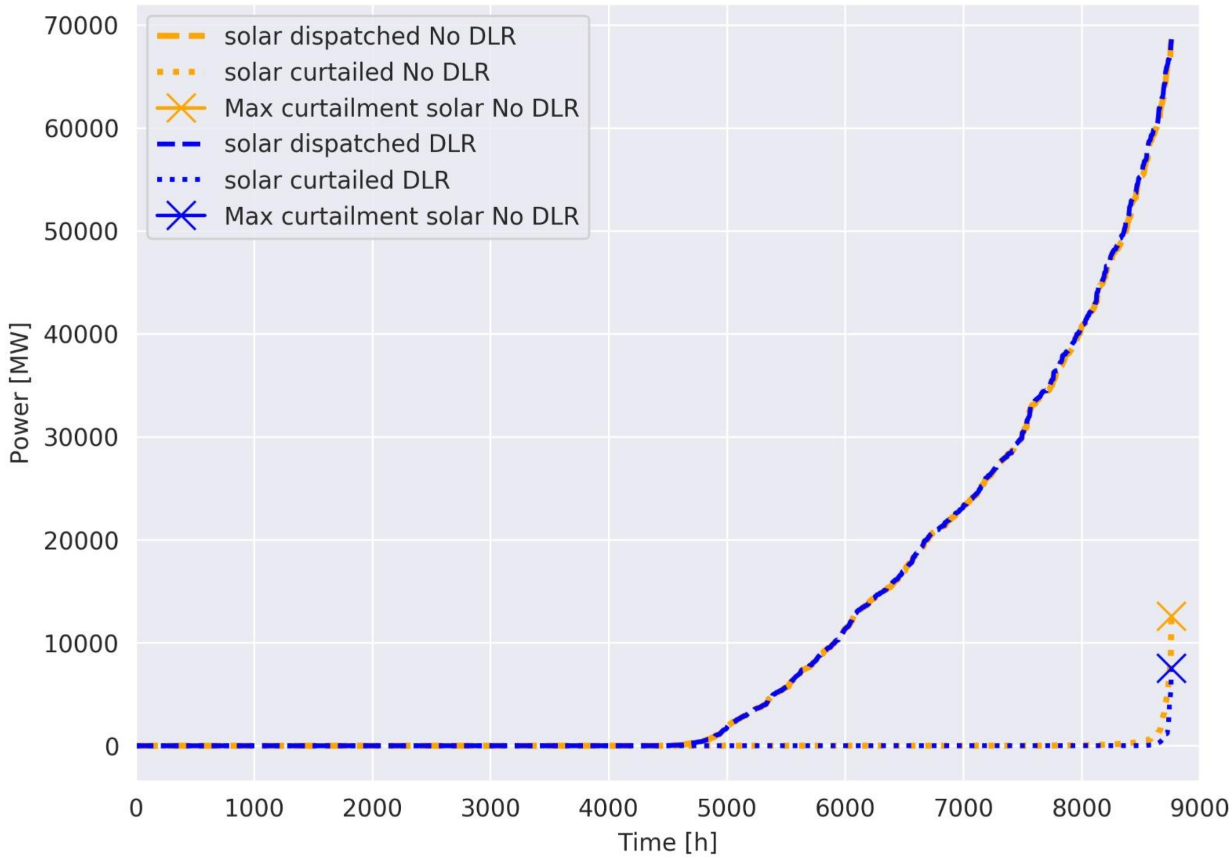

Figure 6-6: Yearly solar PV duration curve for 2011. Source: author

6.3 Biomass dispatch

The reduction in curtailment must generate an effect on biomass dispatch. Biomass power plants have significantly higher operational costs in comparison with solar and wind because they are the only generators that need fuel to work. For this reason, the merit order of biomass is the last in terms of dispatch.

The eGo 100 scenario includes 93.3 GW of biomass installed capacity, of which 27.8 GW are located in Germany. The calculations without DLR estimates that it will be necessary to generate 39.1 TWh by this technology. On the other hand, the calculations using DLR forecast that only 34.4 TWh will have to be generated. It represents a reduction of 12% in energy generated by biomass, which also implies a reduction of the annual system costs that will be analyzed later. To allow a better understanding, the load duration curve for this technology can be observed in Figure 6-7.

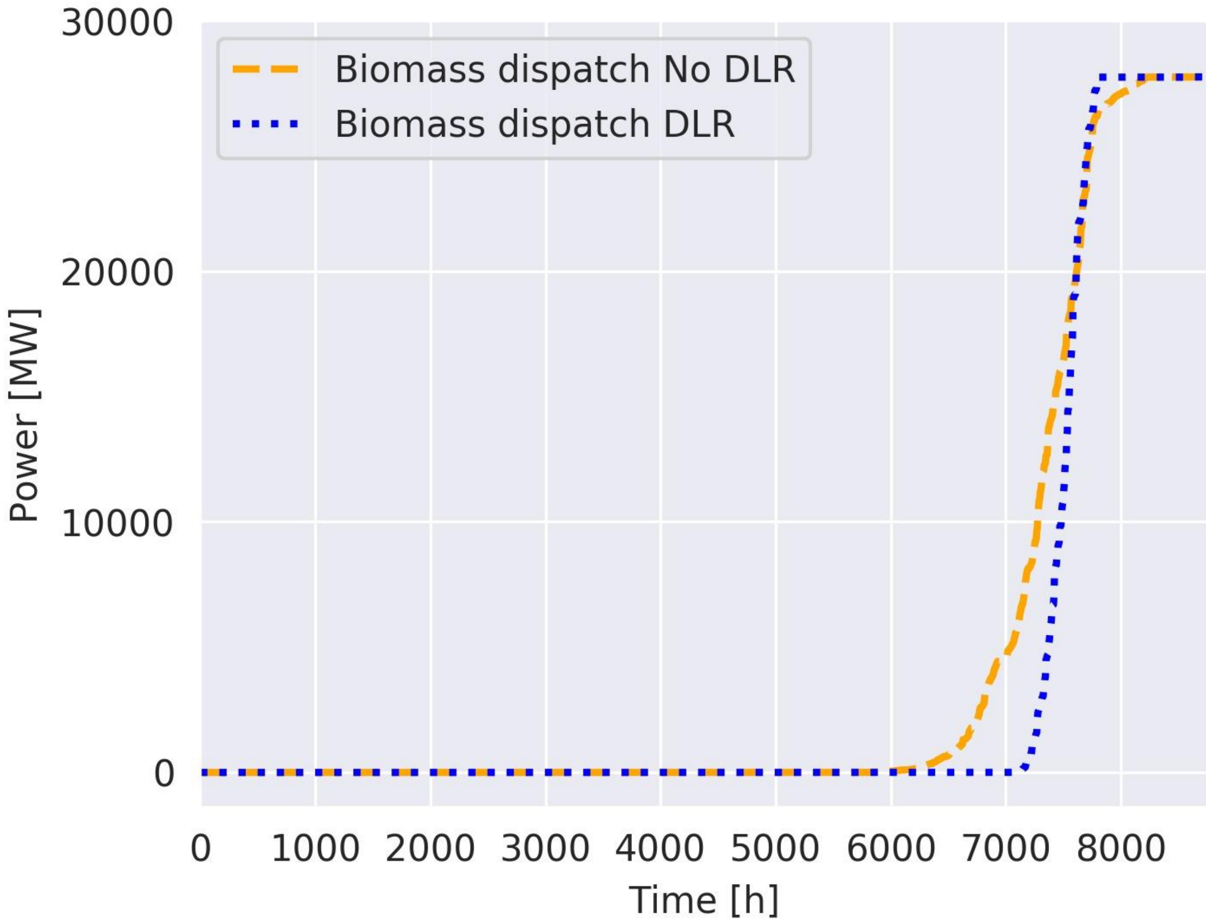

Figure 6-7: Yearly biomass duration curve for 2011. Source: author

6.4 Storage expansion

The last technical aspect that is analyzed as part of this study is the impact of DLR on storage expansion. LOPF in hourly resolution was used to perform this calculation. The optimization function is focused on total system cost. For this reason, it is expected to find small values of storage expansion values due to its high investment cost. It was found that the no DLR scenario required a storage expansion of 520.5 KW with a maximum of 4.8 KW in one single node.

On the other hand, the scenario where the impact of DLR can be seen requires a total storage expansion of 458.4 KW with a maximum of 1.6 KW in one single node. It means a reduction storage expansion of 62.1 KW or 11.9% in comparison with the no DLR calculation. It can be observed graphically in Figure 6-8 the distribution of storage and the comparison between the two scenarios.

Regarding the share of storage technologies, there are very small variations. For the no DLR scenario, 76.9% of the storage is based on batteries, and the remaining 23.1% is based on hydrogen. In contrast, these values are 77.7% and 22.3%, respectively, for the DLR scenario.

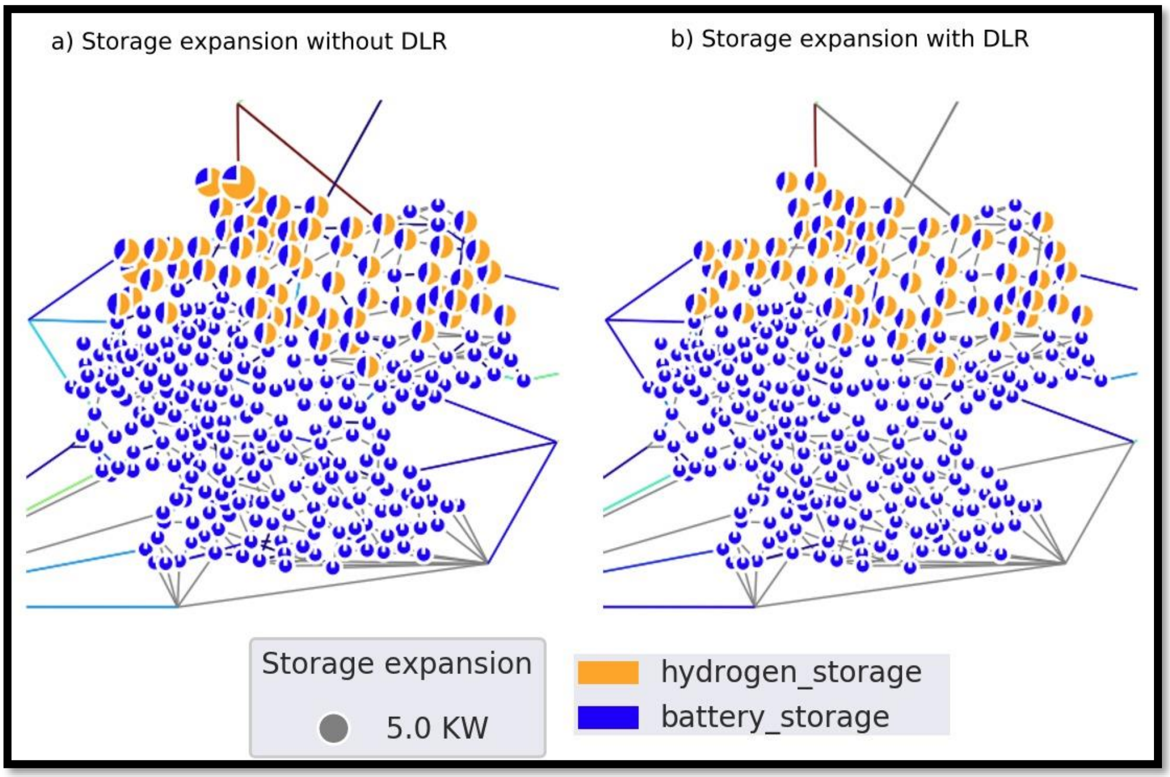

Figure 6-8: Require storage expansion for scenario eGo 100. a) Without DLR. b) With DLR. Source: author

6.5 Total system cost

The total system cost is the main objective of the optimization model. For this reason, the changes presented in the comparison between the scenario with and without using the DLR concept will be the most important of this study. Total annual system costs are the final measure of the impact of DLR on the investment and marginal costs of the system.

It can also be interpreted as the financial implications of the technical aspects analyzed in the previous sections.

The total annual grid investment cost is calculated as the sum of AC and DC investment costs. Regarding the AC investment costs, the analysis shows that it could exist a save of 40.4% if DLR is used. Additionally, no expansion in DC power lines will be necessary. In total, a reduction of 56.4% for grid investment due to the effects of the results presented in section 6.1 can be obtained. The exact values in Euros per year can be found in Table 6-1.

Table 6-1: Comparison of annual grid investment costs. Source: author

Parameter	Scenario No DLR [EUR/a]	Scenario with DLR [EUR/a]	(No DLR - DLR)/ No DLR
AC annual grid investment costs	€ 388,773,833	€ 231,879,246	40.4%
DC annual grid investment costs	€ 143,125,628	€ -	100.0%
Annual grid investment costs	**€ 531,899,461**	**€ 231,879,246**	**56.4%**

Once the annual grid investment cost is calculated, the annual investment costs can be easily calculated by adding the annual storage investment costs. For the scenario eGo 100 and the parameters given for the simulations, the optimal storage capacities presented in section 6.4 represent a very small portion of the annual investments costs. There are no significant differences if DLR is used, and the possible reason for this will be analyzed in the next chapter. The exact values in Euros per year can be found in Table 6-2.

Table 6-2: Comparison of annual investment costs. Source: author

Parameter	Scenario No DLR [EUR/a]	Scenario with DLR [EUR/a]	(No DLR - DLR)/ No DLR
Annual grid investment costs	€ 531,899,461	€ 231,879,246	56.4%
Annual storage investment costs	€ 23,574	€ 20,751	12.0%
Annual investment costs	**€ 531,923,035**	**€ 231,899,996**	**56.4%**

The calculated annual marginal costs are about 549.6 and 439.5 Million Euros per year, which implies a reduction of 20% between scenarios. See Table 6-3.

Finally, the annual system costs are calculated as the sum of the yearly investment costs and the annual marginal costs. The use of DLR could represent a save of 410 Million Euros per year, which means a reduction of 37.9% compared to the no DLR scenario. The exact values in Euros per year can be found in Table 6-3.

Table 6-3: Comparison of annual system costs. Source: author

Parameter	Scenario No DLR [EUR/a]	Scenario with DLR [EUR/a]	(No DLR - DLR)/ No DLR
Annual investment costs	€ 531,923,035	€ 231,899,996	56.4%
Annual marginal costs	€ 549,661,100	€ 439,550,009	20.0%
Annual system costs	**€ 1,081,584,134**	**€ 671,450,005**	**37.9%**

7 Discussion

With the aim of facilitating to the reader the comprehension of the topics addressed throughout this chapter, the analysis of the results presented in chapter 6 will be divided into three main sections: Technical study, economic effect, and social impact. At the end of this chapter, a discussion about the sensibility of the results due to changes in the scenario definition or assumptions regarding market constraints will be held.

7.1 Technical study

The impact of dynamic line rating must be first understood from a technical point of view since it is the starting point to contextualize economic and social consequences. As was anticipated, the most significant changes were found in the network expansion and curtailed energy, but the expansion in storage did not change as much as expected. This unexpected result will be analyzed in section 7.4.

The network expansion represents the most prominent change found in this study. The capacity of just 75 lines will have to be increased compared to the 232 that will have to be modified in the scenario without DLR. Also, the required expansion of these 75 lines is less than the necessary value in the business as usual scenario.

Equation 7-1 is used to measure the reduction in network expansion. This equation takes into consideration the number of transmission lines per scenario, their length, and the additional capacity that each transmission line requires in each scenario.

$$Ne_{reduction} = 1 - \frac{\sum_{i=0}^{m} D\_Le_i * D\_Ll_i}{\sum_{i=0}^{n} ND\_Le_i * ND\_Ll_i}$$

Equation 7-1: Network expansion reduction

Where:

n: number of lines that require network expansion in the No DLR scenario

m: number of lines that need network expansion in the DLR scenario

ND_Le_i: network expansion for the i-line in the No DLR scenario

D_Le_i: network expansion for the i-line in the DLR scenario

ND_Ll_i: length of the i-line in the No DLR scenario

D_Ll_i: length of the i-line in the DLR scenario

By using the methodology described in Equation 7-1, it can be said that applying the concept of DLR has the potential to decrease by **41.1%** the necessity of expansion of the German electric grid.

Since the DLR calculated values are different for the nine regions shown in Figure 3-1, the benefits on account of DLR also vary geographically. The west part of the country has a more extensive electric infrastructure in terms of transmission lines (Figure 5-3) and demand (Figure 5-1). The grid expansion is also higher in this area, as shown in Figure 6-1. Around Hamburg, Dortmund, Frankfurt, and Stuttgart, the number of transmission lines that must be modified due to the network necessities is exceptionally high. This number drops dramatically when DLR is used. The mentioned places are located in regions 1, 3, and 5, which have average DLR scores of 1.30, 1.28, and 1.25, respectively.

In general, it can be said that the effect of DLR on the network expansion was boosted by the coincidence of the high density of objective lines in regions with high DLR average values.

Curtailment is another measure that worths mentioning. From the theoretical point of view, assigning a bigger capacity to a transmission line would allow it to transport more current during peak generation periods. It would decrease or even delete the energy associated tot that line which is not generated because of network constraints. When this concept is applied to an entire network, and the objective is to calculate future grid requirements based on minimizing annual system cost, the analysis becomes more complex., the evaluation can be done by type of technology as presented in chapter 6 to make it more precise.

From the methodology to calculate DLR can be interpreted that there will be a benefit for all the different kind of variable renewable energies. Still, it is different for each one of them. Since DLR values increase with higher wind speeds, it is evident that peak generation of wind power will coincide with highly favorable instant transmission capacity.

It is not the case of solar PV, which has its peak generation periods when the solar irradiation is maximum and, therefore, most likely the temperature.

Dynamic line rating was calculated only for lines inside Germany, but the entire simulated system includes interconnections to neighbor countries. Consequently, curtailment can be calculated for the complete 300 nodes grid or just for the generators connected to nodes inside the country. Both values were calculated and analyzed, and it was found that the curtailment values barely vary compared to the No DLR scenario when the grid outside Germany is considered. In contrast, there are significant variations when the scope is the generators inside Germany.

Regarding wind onshore, the yearly curtailed energy decreases from 3.1 GWh to 0.81 GWh. It represents a reduction of 73.6% in comparison. It is an outstanding value that can be easily explained by the relation between wind speed and DLR. On the subject of wind offshore, the findings are even more prominent. The energy not produced because of network constraints reduces from 10.3 GWh to 0.15 GWh for the analysis year. This vast difference can be attributed to the location of the offshore wind farms. All of them are built in the very north of the country, in regions 1 and 2, where the average DLR values are the highest (1.3 and 1.32, respectively).

Changes for solar PV generators are less outstanding but still beneficial for their integration. The curtailed energy dropped from 0.7 GWh to 0.22 GWh per year. In any case, the curtailed energy is not very significant, presumably due to its proximity in many instances to the load.

7.2 Economic effect

Regarding financial implications, the impart of DLR should be analyzed from 2 different perspectives: investment and marginal costs, which are the components to calculate the annual system costs.

The annual investment costs are the sum of the grid investment and storage investment costs. The simulation using the parameters presented at the beginning of chapter 6 shows that the storage investment is minimal compared to the grid investment. Therefore, the reduction of 12% for this item is not significant for the final 56.4% saving in annual investment costs. Consequently, almost all the savings are the result of the reduction in network expansion. This conclusion is highly sensitive to parameter changes like constraints for energy exchange with neighboring countries, as will be presented in section 7.4.

The reduction in marginal costs can be attributed to two different factors. The first one is the reduction in curtailment, which allows the system to receive and use more energy generated from sources with virtually zero operational costs. For solar PV generators, it does not represent a significant change, but in wind power, a total of 12.44 additional TWh are integrated into the grid. To keep the balance between generation and consumption, the extra energy must be compensated with an increment of exported/decrease of imported electricity. It is also expected that the most expensive and regulable type of generator available decreases its production. In the case of the eGo 100 scenario, that generator is biomass.

Biomass power plants presented a reduction of 4.7 TWh in energy generated for the studied year when DLR was used. It can explain in a considerable proportion the fall of 20% in annual marginal costs.

In general, a total save in annual investment costs of 37.9% can be achieved, but there are some limitations. These results are calculated based on the assumption of using DLR for every overhead transmission line in Germany, but whether to apply it or not in a particular region or transmission line is an entirely different discussion. Additionally, the cost of implementation of DLR is out of the scope of this study but must be discussed to reach a reliable conclusion.

7.3 Social impact

From a social point of view, the impact of DLR could be explained in two main particulars: the future cost of electricity and the level of rejection of new grid infrastructure. Regarding the first one, it could be anticipated that using DLR will create the conditions to have electricity costs about 38% lower in comparison with the conventional scenario. It is a direct consequence that will benefit every household and could give better conditions to incentivize the industry sector.

Additionally, despite a general approval of the promotion of alternative energies by the German population (Agentur für Erneuerbare Energien, 2014), infrastructure measures affecting the landscape are facing increasing public opposition at local levels. This is evident especially in the case of the electricity transmission grid expansion (Wohlgemuth, 2016). The degree of rejection increases with the number of new transmission lines required, even if it is of general knowledge that they are built to provide a service.

In this way, decreasing the number of new transmission lines will affect the landscape in a smaller proportion and avoid unnecessary increment of opposition to new electric infrastructure. In the end, it will facilitate the conditions to achieve a system based on 100% renewable energy, which contributes directly to the general wellbeing of society.

7.4 The sensibility of the results

As mentioned in the previous section, even if the same scenario is used, the results are sensitive to changes in the simulation parameters. A second simulation was run to demonstrate how different the outputs can be. This section can not be considered as a sensibility study since it is no part of the scope.

For the purpose of having an output with a broader inclusion of storage in the grid, the parameter *capacity* for *foreign lines* is changed. For the previous simulation, this parameter was set as osmTGmod, and the new one will be *ntc_acer*. Next, their main characteristics are presented regarding cross-border capacities.

- **osmTGmod** is the acronym for Open Street Map (OSM) and Transmission Grid Model is a load-flow model of the German transmission-gird, based on the free geodatabase OpenStreetMap (Scharf and Nebel, 2016). Using osmTGmod assigns transmission capacities found on physical characteristics to the transmission lines which connect the German electric grid to the neighboring countries. No other constraints than the electric attributes of the infrastructure are considered.

- **ntc_acer** is the acronym for Net Transfer Capacity methodology (NTC) created by the Agency for the Cooperation of Energy Regulators (ACER). This agency aims to develop guidelines for the calculation and allocation of cross-zonal transmission lines' capacities for the completion of the internal European electricity market. The main objective of the rules mentioned above is efficient management of network congestions, for instance, circumstances when the capacity of a network is not enough to accommodate all requests for transmission over this network. Efficient managing of network congestions consists of network development and investments, the definition of bidding zones, calculation and allocation of cross-zonal capacities in different timeframes, and, finally, identification of remaining congestions, which need to be addressed with remedial actions such as redispatching (Agency for the Cooperation of Energy Regulators, 2020).

In this way, the assigned capacities for the foreign transmission lines are based on regulations following the described objective. These capacities are considerably lower than the ones provided by osmTGmod.

The simulation done using the net transfer capacity methodology kept all the other parameters invariable to make the results comparable. Additionally, the same base grid generated for the original simulation (Figure 5-7) was used. It is essential to highlight that even keeping intact all the other parameters, the outputs for the no DLR scenario for both simulations will be different. In favor of clarity, from now on, the original simulation will be called osmTGmod, and the new ntc_acer.

The same outputs were analyzed for both simulations. Mainly, all the studied factors show significant differences. The new capacities of transmission lines for energy exchange with neighboring countries in the ntc_acer simulation create a condition where considerably less energy is financially worthy or possible to spread via grid expansion inside of Germany. For this reason, a massive amount of storage expansion is needed in comparison with the osmTGmod simulation. A complete summary of the most relevant finding can be found in Table 7-1.

Table 7-1: Comparison of simulations with different constraints for energy exchange with neighboring countries. Source: author

	OsmTGmod		NTC ACER	
	No DLR	DLR	No DLR	DLR
Lines that require expansion	234	75	90	34
Network expansion reduction [%]	-	0.59	-	0.74
Curtailment – wind onshore [TWh]	3.1	0.8	10.9	9.3
Curtailment – wind offshore [TWh]	10.4	0.2	10.0	2.8
Curtailment – solar PV [TWh]	0.7	0.2	3.0	2.5
Energy biomass [TWh]	39.2	34.5	74.5	59.9
Storage expansion [MW]	0.52	0.46	3221.6	3985.1
Annual investment costs [MEUR/year]	531.9	231.9	393.9	399.9
Annual marginal costs [MEUR/year]	549.7	439.6	1229.5	1054.4
Annual grid investment costs [MEUR/year]	531.9	231.9	240.3	209.5
AC annual grid investment costs [MEUR/year]	388.8	231.9	109.9	79.1
DC annual grid investment costs [MEUR/year]	143.1	0.0	130.4	130.4
Annual storage investment costs [MEUR/year]	0.024	0.021	153.5	190.4
Annual system costs [MEUR/year]	1081.6	671.5	1623.4	1454.3

Another difference that is important to mention is the increment in marginal costs. It results mainly from the growth in biomass generation and the impossibility to export/import excedents of wind or solar PV power to/from other countries. Also, network expansion decreased, presumably because the energy exchange was reduced and some energy will not be transported but curtailed.

Given the previous results and explanations, it is clear that measuring the impact of using the DLR concept is very susceptible to the selected parameters and many other factors. It does not mean that the results presented here are wrong, but they can be subject to changes.

8 Conclusions

The most immediate observable result of DLR is the increment of the transmission lines capacities. Even under a very conservative methodology like the one used for this study, the lowest average transmission capacity increased by 20%. In the north of Germany, this value reached a maximum of 32% (Figure 4-3). Considering the new dynamic capacities, the effect on the network expansion is remarkable. For the eGo 100 scenario, the network expansion requirements dropped around 41%. It represents a save of approximately 300 million Euros per year.

Since network congestion is a big problem for integrating variable renewable energy, DLR creates the technical conditions to incorporate solar and wind farms into the system by diminishing curtailment. Wind power generators receive the most significant benefit. Onshore wind farms' curtailment dropped from 3.1 TWh to 0.81 TWh, while offshore wind farms' curtailment fell from 10.3 TWh to 0.15 TWh. In solar PV, there is a reduction of curtailment, but it is not as significant as it is for wind power.

Part of energy that is curtailed in the scenario without DLR is extra energy flowing into the network using the new transmission capacities. It has a direct impact on power exchange with the neighboring countries and the generation mix. About the second, the effect is directly in the total energy produced by biomass generators. There is a reduction of 4.7 TWh in biomass energy, representing 12% of the total energy generated by this technology in the scenario without DLR.

As presented in section 7.4, the assumptions used for the simulations can significantly affect the results. For instance, one of the objectives of this study was to calculate the impact of DLR on the amount of required storage. According to the results shown in chapter 6, there was a reduction of 11.9% in storage expansion. Still, after performing the simulation using different conditions for the capacity of the transmission lines connecting Germany to other countries, these results have a considerable difference.

The annual investment costs (network expansion + storage expansion) dropped about 56%. On the other hand, the yearly marginal costs decreased around 20%. The annual system costs are approximately 671 Million Euros per year, 37.9% less than the scenario without DLR.

In terms of social impact, a lower total annual system cost will also represent a lower energy cost for households and industry compared to the scenario without DLR. Additionally, a decrease in network expansion requirements means that the new transmission lines will affect in a lower proportion the landscape. This can also be interpreted as a lower social level of rejection against the necessary infrastructure to achieve the goals related to integrating non-conventional energies sources.

9 Outlook

During the development of this work, the technical, economic, and social potential impact of using the concept of DLR were analyzed. There are related topics that were out of the scope but should be investigated to complement the research presented in this work

Implementation of DLR represents a complex technical challenge, and there are several proposals about the most suitable way to put it into service (Castel, 2015). The evaluation and selection of the most appropriate methodology for the German case is a primary future task. Furthermore, the cost of implementing DLR must be calculated and taken into account to find net economic benefits. Additionally, risks related to the impact of global warming on the expected added transmission capacity must be analyzed.

The results presented in this document consider that DLR is calculated for every overhead transmission line inside Germany. It is an assumption for academic purposes, but a more detailed analysis would likely find this excessive. A future exhaustive study should find a balanced technical-economic optimal solution. Finally, a sensibility analysis must be developed. As it was shown, the results depend significantly on the selected simulation parameters, but the range was not established.

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11 Appendixes

11.1 Histograms for DLR per region

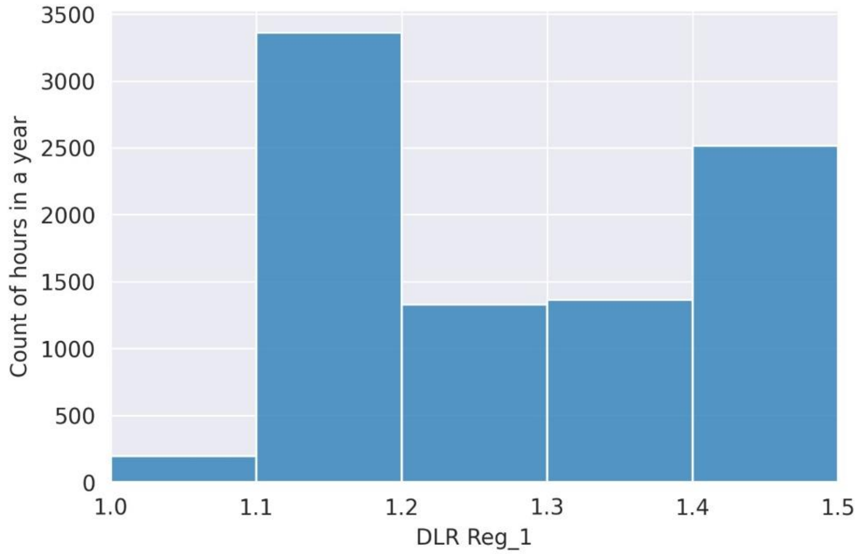

Figure 11-1: DLR histogram region_1 in a representative year. Source: author

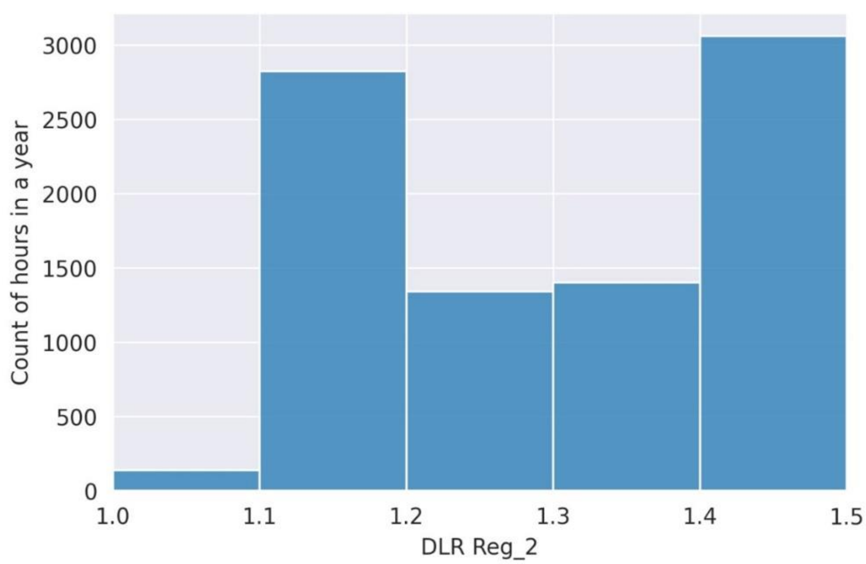

Figure 11-2: DLR histogram region_2 in a representative year. Source: author

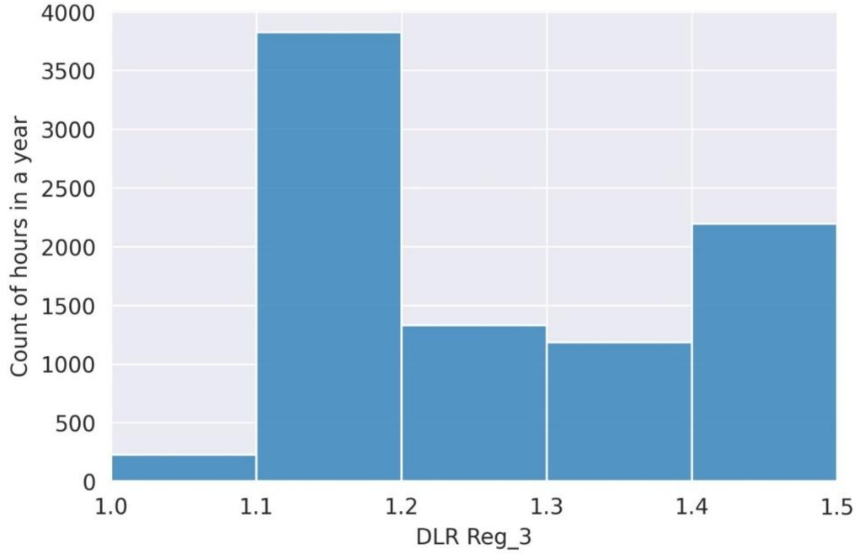

Figure 11-3: DLR histogram region_3 in a representative year. Source: author

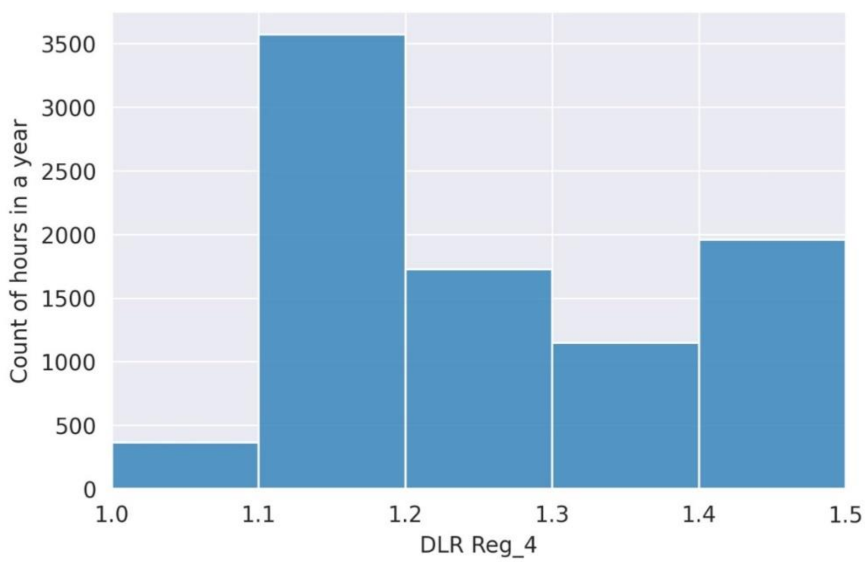

Figure 11-4: DLR histogram region_4 in a representative year. Source: author

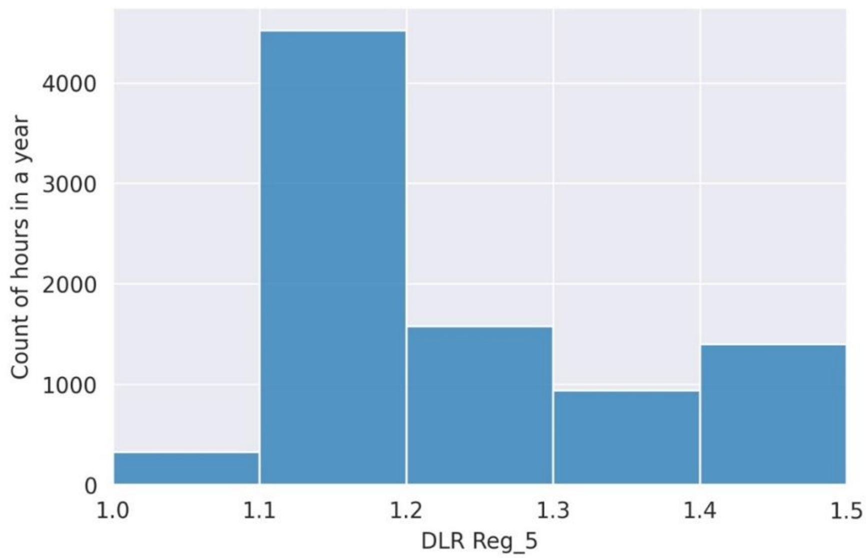

Figure 11-5: DLR histogram region_5 in a representative year. Source: author

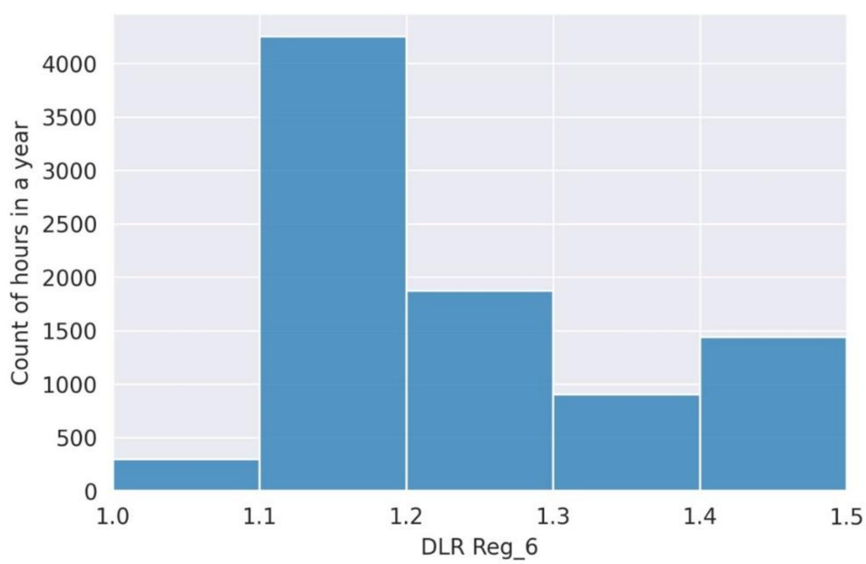

Figure 11-6: DLR histogram region_6 in a representative year. Source: author

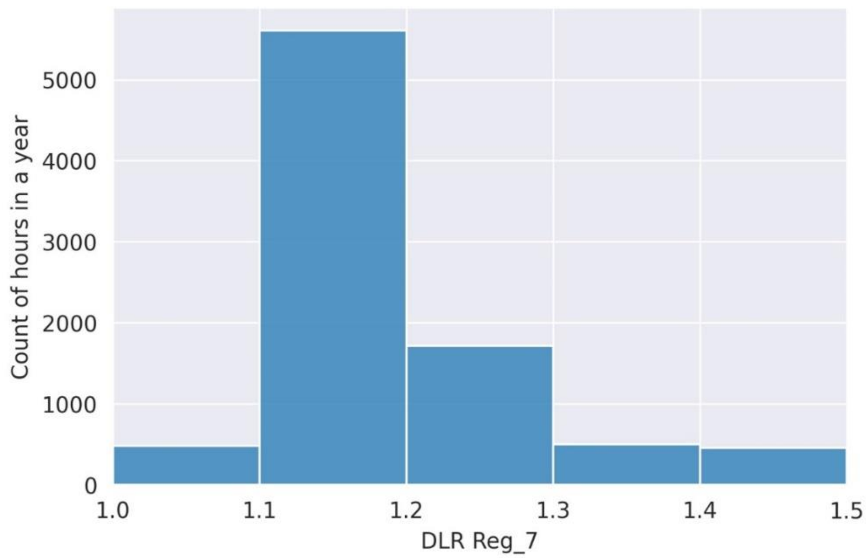

Figure 11-7: DLR histogram region_7 in a representative year. Source: author

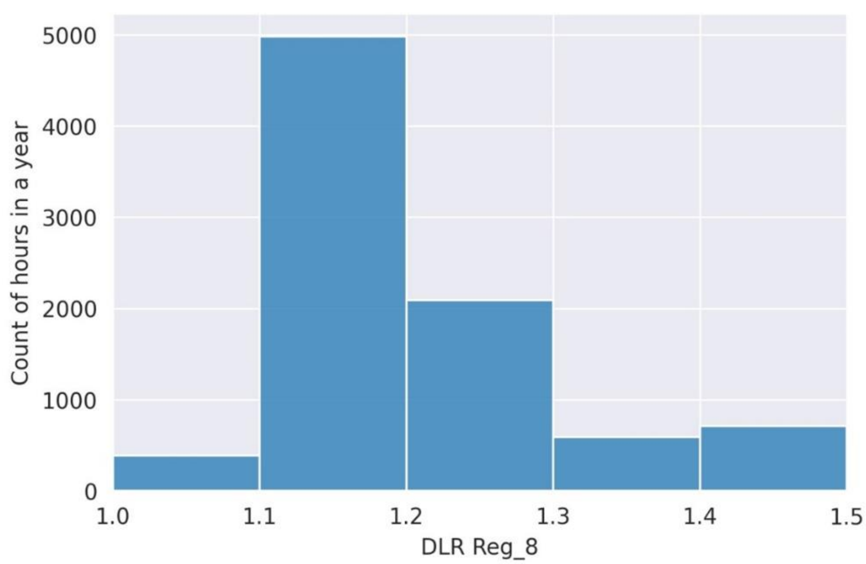

Figure 11-8: DLR histogram region_8 in a representative year. Source: author

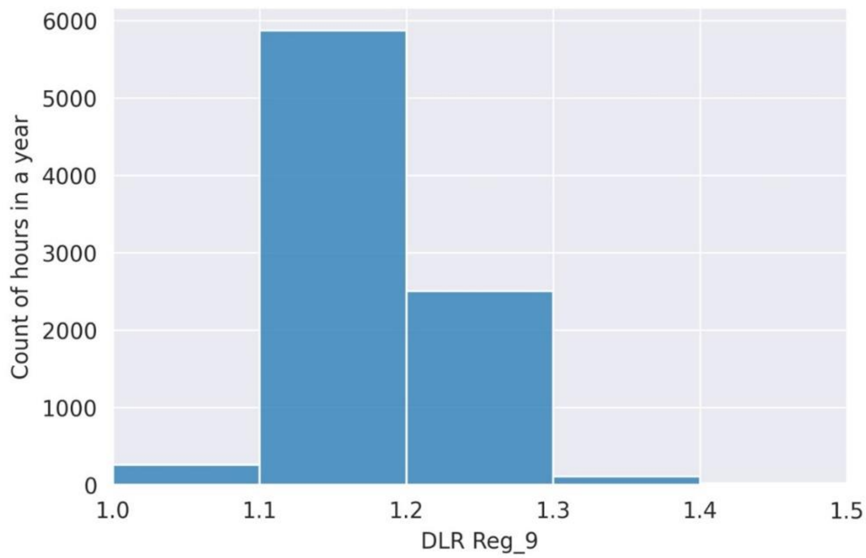

Figure 11-9: DLR histogram region_9 in a representative year. Source: author

11.2 DLR code

```
"""
Use the concept of dynamic line rating(DLR) to calculate temporal
depending capacity for HV transmission lines.
Inspired mainly on Planungsgrundsaetze-2020
Available at:
<https://www.transnetbw.de/files/pdf/netzentwicklung/netzplanungsgrundsaetze/
UENB_PlGrS_Juli2020.pdf>
"""
import geopandas as gpd
import pandas as pd
import numpy as np
from egon.data import db
import xarray as xr
import rioxarray
from shapely.geometry import Point
import psycopg2


def Calculate_DLR():
    """Calculate DLR and assign values to each line in the db

    Parameters
    ----------
    *No parameters required

```

```
    """

    weather_info_path = "cutouts/europe-2011-era5/201101.nc"
    regions_shape_path = (
        "data_bundle_egon_data/regions_dynamic_line_rating/Germany_regions.shp"
    )

    # Calculate hourly DLR per region
    dlr_hourly_dic, dlr_hourly = DLR_Regions(weather_info_path, regions_shape_path)

    regions = gpd.read_file(regions_shape_path)
    regions = regions.sort_values(by=["Region"])

    # Connect to the data base
    con = db.engine()

    sql = "SELECT version, scn_name, line_id, geom, s_nom FROM grid.egon_pf_hv_line"
    df = gpd.GeoDataFrame.from_postgis(sql, con, crs="EPSG:4326")

    trans_lines_R = {}
    for i in regions.Region:
        shape_area = regions[regions["Region"] == i]
        trans_lines_R[i] = gpd.clip(df, shape_area)
    trans_lines = df[["s_nom"]]
    trans_lines["in_regions"] = [[] for i in range(len(df))]

    trans_lines[["line_id", "geometry", "version", "scn_name"]] = df[
        ["line_id", "geom", "version", "scn_name"]
    ]

    # Assign to each transmission line the region to which it belongs
    for i in trans_lines_R:
        for j in trans_lines_R[i].index:
            trans_lines.loc[j][1] = trans_lines.loc[j][1].append(i)

    DLR = []
    # Assign to each transmision line the final values of DLR based on location
    # and type of line (overhead or underground)
    for i in trans_lines.index:
        # lines completely out of the Germany border have DLR = 1
```

```
        if len(trans_lines.loc[i][1]) == 0:
            DLR.append([1] * 8760)
            continue
        # Underground lines have DLR = 1
        if (
            trans_lines.loc[i][0] % 280 == 0
            or trans_lines.loc[i][0] % 550 == 0
            or trans_lines.loc[i][0] % 925 == 0
        ):
            DLR.append([1] * 8760)
            continue
        # Lines completely in one of the regions, have the DLR of the region
        if len(trans_lines.loc[i][1]) == 1:
            region = int(trans_lines.loc[i][1][0])
            DLR.append(dlr_hourly_dic["R" + str(region) + "-DLR"])
            continue
        # For lines crossing 2 or more regions, the lowest DLR between the
        # different regions per hour is assigned.
        if len(trans_lines.loc[i][1]) > 1:
            reg = []
            for j in trans_lines.loc[i][1]:
                reg.append("Reg_" + str(j))
            min_DLR_reg = dlr_hourly[reg].min(axis=1)
            DLR.append(list(min_DLR_reg))

    trans_lines["s_max_pu"] = DLR

    # delete unnecessary columns
    trans_lines.drop(columns=["in_regions", "s_nom", "geometry"], inplace=True)

    # Modify column "s_max_pu" to fit the requirement of the table
    trans_lines["s_max_pu"] = trans_lines.apply(lambda x: list(x["s_max_pu"]), axis=1)
    trans_lines["temp_id"] = 1
    # Insert into database
    trans_lines.to_sql(
        "egon_pf_hv_line_timeseries",
        schema="grid",
        con=db.engine(),
        if_exists="append",
        index=False,
    )
    return 0
```

```


def DLR_Regions(weather_info_path, regions_shape_path):
    """Calculate DLR values for the given regions

    Parameters
    ----------
    weather_info_path: str, mandatory
        path of the weather data downloaded from ERA5
    regions_shape_path: str, mandatory
        path to the shape file with the shape of the regions to analyze

    """

    # load, index and sort shapefile with the 9 regions defined by NEP 2020
    regions = gpd.read_file(regions_shape_path)
    regions = regions.set_index(["Region"])
    regions = regions.sort_values(by=["Region"])

    # The data downloaded using Atlite is divided by months. Paths_weather stores
    # the paths of the 12 files to be loaded together in 'weather_data_raw'.
    paths_weather = []
    for i in range(1, 13):
        paths_weather.append("cutouts/europe-2011-era5/2011" + str(i).zfill(2) + ".nc")

    weather_data_raw = xr.open_mfdataset(paths_weather)
    weather_data_raw = weather_data_raw.rio.write_crs(4326)
    weather_data_raw = weather_data_raw.rio.clip_box(
        minx=5.5,
        miny=47,
        maxx=15.5,
        maxy=55.5,
    )

    wind_speed_raw = weather_data_raw.wnd100m.values
    temperature_raw = weather_data_raw.temperature.values
    roughness_raw = weather_data_raw.roughness.values
    index = weather_data_raw.indexes._indexes
    # The info in 'weather_data_raw' has 3 dimensions. In 'weather_data' will be
    # stored all the relevant data in a 2 dimensions array.
    weather_data = np.zeros(shape=(wind_speed_raw.size, 5))
```

```python
    count = 0
    for hour in range(index["time"].size):
        for row in range(index["y"].size):
            for column in range(index["x"].size):
                rough = roughness_raw[hour, row, column]
                ws_100m = wind_speed_raw[hour, row, column]
                # Use Log Law to calculate wind speed at 50m height
                ws_50m = ws_100m * (np.log(50 / rough) / np.log(100 / rough))
                weather_data[count, 0] = hour
                weather_data[count, 1] = index["y"][row]
                weather_data[count, 2] = index["x"][column]
                weather_data[count, 3] = ws_50m
                weather_data[count, 4] = temperature_raw[hour, row, column] - 273.15
                count += 1

    weather_data = pd.DataFrame(
        weather_data, columns=["hour", "lat", "lon", "wind_s", "temp"]
    )

    region_selec = weather_data[0 : index["x"].size * index["y"].size].copy()
    region_selec["geom"] = region_selec.apply(
        lambda x: Point(x["lon"], x["lat"]), axis=1
    )
    region_selec = gpd.GeoDataFrame(region_selec)
    region_selec = region_selec.set_geometry("geom")
    region_selec["region"] = np.zeros(index["x"].size * index["y"].size)

    # Mask weather information for each region defined by NEP 2020
    for reg in regions.index:
        weather_region = gpd.clip(region_selec, regions.loc[reg][0])
        region_selec["region"][region_selec.isin(weather_region).any(axis=1)] = reg

    weather_data["region"] = region_selec["region"].tolist() * index["time"].size
    weather_data = weather_data[weather_data["region"] != 0]

    # Create data frame to save results(Min wind speed, max temperature and %DLR per region along 8760h in a year)
    time = pd.date_range("2011-01-01", "2011-12-31 23:00:00", freq="H")
    # time = time.transpose()
    dlr = pd.DataFrame(
        0,
        columns=[
            "R1-Wind_min",
```

```
            "R1-Temp_max",
            "R1-DLR",
            "R2-Wind_min",
            "R2-Temp_max",
            "R2-DLR",
            "R3-Wind_min",
            "R3-Temp_max",
            "R3-DLR",
            "R4-Wind_min",
            "R4-Temp_max",
            "R4-DLR",
            "R5-Wind_min",
            "R5-Temp_max",
            "R5-DLR",
            "R6-Wind_min",
            "R6-Temp_max",
            "R6-DLR",
            "R7-Wind_min",
            "R7-Temp_max",
            "R7-DLR",
            "R8-Wind_min",
            "R8-Temp_max",
            "R8-DLR",
            "R9-Wind_min",
            "R9-Temp_max",
            "R9-DLR",
        ],
        index=time,
    )

    # Calculate and save min wind speed and max temperature in a dataframe.
    # Since the dataframe generated by the function era5.weather_df_from_era5() is sorted by date,
    # it is faster to calculate the hourly results using blocks of data defined by "step", instead of
    # using a filter or a search function.
    for reg, df in weather_data.groupby(["region"]):
        for t in range(0, len(time)):
            step = df.shape[0] / len(time)
            low_limit = int(t * step)
            up_limit = int(step * (t + 1))
            dlr.iloc[t, 0 + int(reg - 1) * 3] = min(df.iloc[low_limit:up_limit, 3])
            dlr.iloc[t, 1 + int(reg - 1) * 3] = max(df.iloc[low_limit:up_limit, 4])
```

```
    # The next loop use the min wind speed and max temperature calculated previously to
    # define the hourly DLR in for each region based on the table given by NEP 2020 pag 31
    for i in range(0, len(regions)):
        for j in range(0, len(time)):
            if dlr.iloc[j, 1 + i * 3] <= 5:
                if dlr.iloc[j, 0 + i * 3] < 3:
                    dlr.iloc[j, 2 + i * 3] = 1.30
                elif dlr.iloc[j, 0 + i * 3] < 4:
                    dlr.iloc[j, 2 + i * 3] = 1.35
                elif dlr.iloc[j, 0 + i * 3] < 5:
                    dlr.iloc[j, 2 + i * 3] = 1.45
                else:
                    dlr.iloc[j, 2 + i * 3] = 1.50
            elif dlr.iloc[j, 1 + i * 3] <= 15:
                if dlr.iloc[j, 0 + i * 3] < 3:
                    dlr.iloc[j, 2 + i * 3] = 1.20
                elif dlr.iloc[j, 0 + i * 3] < 4:
                    dlr.iloc[j, 2 + i * 3] = 1.25
                elif dlr.iloc[j, 0 + i * 3] < 5:
                    dlr.iloc[j, 2 + i * 3] = 1.35
                elif dlr.iloc[j, 0 + i * 3] < 6:
                    dlr.iloc[j, 2 + i * 3] = 1.45
                else:
                    dlr.iloc[j, 2 + i * 3] = 1.50
            elif dlr.iloc[j, 1 + i * 3] <= 25:
                if dlr.iloc[j, 0 + i * 3] < 3:
                    dlr.iloc[j, 2 + i * 3] = 1.10
                elif dlr.iloc[j, 0 + i * 3] < 4:
                    dlr.iloc[j, 2 + i * 3] = 1.15
                elif dlr.iloc[j, 0 + i * 3] < 5:
                    dlr.iloc[j, 2 + i * 3] = 1.20
                elif dlr.iloc[j, 0 + i * 3] < 6:
                    dlr.iloc[j, 2 + i * 3] = 1.30
                else:
                    dlr.iloc[j, 2 + i * 3] = 1.40
            elif dlr.iloc[j, 1 + i * 3] <= 35:
                if dlr.iloc[j, 0 + i * 3] < 3:
                    dlr.iloc[j, 2 + i * 3] = 1.00
                elif dlr.iloc[j, 0 + i * 3] < 4:
                    dlr.iloc[j, 2 + i * 3] = 1.05
```

```
                elif dlr.iloc[j, 0 + i * 3] < 5:
                    dlr.iloc[j, 2 + i * 3] = 1.10
                elif dlr.iloc[j, 0 + i * 3] < 6:
                    dlr.iloc[j, 2 + i * 3] = 1.15
                else:
                    dlr.iloc[j, 2 + i * 3] = 1.25
            else:
                dlr.iloc[j, 2 + i * 3] = 1.00

    DLR_hourly_df_dic = {}
    for i in dlr.columns[range(2, 29, 3)]:  # columns with DLR values
        DLR_hourly_df_dic[i] = dlr[i].values

    dlr_hourly = pd.DataFrame(index=time)
    for i in range(len(regions)):
        dlr_hourly["Reg_" + str(i + 1)] = dlr.iloc[:, 3 * i + 2]

    return DLR_hourly_df_dic, dlr_hourly
```

12 Declaration/Affidavit

I hereby expressly declare that I have prepared this work on my own using no sources, aids or resources other than those cited in it. In particular, I expressly affirm that I have not used any services or received support of any kind, paid or unpaid, from ghost-writer agencies, comparable service providers, or other third parties. All text passages cited or borrowed (either verbatim or in spirit) from printed, electronic or other sources have been duly acknowledged by me.

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Flensburg, 13.08.2021

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