TECHNICAL UNIVERSITY OF VIENNA
UNIVERSITY OF ZAGREB

MASTER THESIS No. 2282

REPOWERING OF WIND PLANTS: WHAT IS POSSIBLE UP TO 2030 AND 2050 IN AUSTRIA?

Klara Krkalović

Supervisors:

PRIV.-DOZ. DIPL.-ING. DR. AMELA AJANOVIC

IZV. PROF. DR. SC. TOMISLAV CAPUDER

Vienna, July 2021.

Abstract

The repowering of wind power plants contributes to the increment of renewable energy resources (RES) in the Austrian energy mix to obtain national energy targets. This thesis examines the possible capacity potentials and cost reductions due to repowering up to 2030 and 2050, considering the age structure and locations of existing wind power plants. Data regarding Austrian wind installations is collected and through economic analysis a moment for repowering is established. Future values of wind capacity, annual energy production, and possible curtailments are determined by applying specific optimization constraints. Furthermore, investment and operation and maintenance costs are calculated using a technological learning mechanism. Obtained results show that there are beneficial outcomes of the repowering process, as the growth of wind energy production and the decrement of wind technology costs.

Keywords: RES, wind energy, repowering, technological learning, optimization

Contents

1. Introduction

Being clean, free, and widely available, the wind is one of the most promising energy sources. Due to its great characteristics, wind technology is experiencing significant growth and development. Turbines generate electricity by capturing wind energy, that is why wind power production does not directly emit greenhouse gases, which makes it sustainable [1]. The wind has an important role in dealing with climate changes and managing the problem of electricity demand increment [2]. Another advantage of wind energy is that it is cost-effective and one of the lowest-priced energy sources in many regions [3].

Despite the many good features, wind power is still facing some challenges. For example, conventional power plants have better chances in the electricity market. Best wind sites are located far away from the demand, requiring expenses for long transmission lines. Moreover, wind turbines cause noise and have a visual impact and an effect on wildlife [3]. Lowering these impacts is supported by development through technological learning. Consequently, making wind technology more effective, cheaper, and less influential to the environment [4].

European wind energy generation in 2020 covered about 16% of total Europe’s electricity demand, with more than 200 GW installed [5]. In Austria, at the end of 2020, there were 1300 wind turbines installed with a total output of 3,12 GW. The generation of these plants corresponds to the electricity demand of about 50% of all Austrian households [6].

The lifetime of the installed wind plants in Austria is coming to an end, which opens the possibility for repowering instead of just decommissioning the plant. Through repowering, wind turbines are replaced by the more powerful and more efficient ones [7]. It brings advantages like the increment of the total installed wind power capacity, reduction in the number of turbines, quieter and modern turbines with fewer maintenance requirements [8].

This work examines the question of optimal timing for repowering wind parks in Austria. To discover that, the lifetime and location of existing parks are considered, together with the parameters which determine the moment of repowering. Possible wind capacity potentials due to repowering up to 2030 and 2050 are analyzed, and how will this change affect the investment and operation and maintenance (O&M) costs of wind technologies. Additionally, it is explored if there will to be some wind curtailments due to the production growth in the future. The applied method uses economic and technical constraints and optimizations to achieve the results.

After the introduction, state-of-the-art is presented in the second chapter discussing already existing publications related to this topic and how this work connects with it. The third chapter illustrates the current situation of wind power in Austria. The next chapter states what essentially repowering is and what conditions and benefits it brings along. The fifth chapter describes the methodological approach. Data and tools are listed and described. Similarly, equations and assumptions are introduced. The sixth chapter of this work reveals the obtained results: repowering timing, increment in capacities and energy, possible curtailments, and cost changes. Sensitivity analysis is done based on the achieved results. The last chapter provides fundamental conclusions of the thesis.

2. State of the art

Repowering of wind turbines is widely used, and many scientific works are already dedicated to this topic. Examples and case studies of repowering were conducted in different parts of the world: in Tunisia [8], [9], Sweden [10], UK [11], Spain [12], [7], and so on. It is considered that the repowering of wind plants in Denmark, Germany, Spain, and California strongly contributed to the development of the repowering process [13]. In the literature different effects of repowering were analyzed: technological [14], environmental [15], economic, and timing effects [16]. Authors in document [10] also analyze many aspects of repowering: energy aspect, economic, local, technological, and so on. In [2] reasons to use synchronous generators in the repowering process are shown.

As well, more and more offshore wind power plants are being repowered. Research about optimization regarding topology and repowering time of offshore wind parks has been conducted [17], [18], [19].

The process of technological learning strongly contributed to the development and use of the repowering for wind plants. Even though it has been known for years in the field of energy technologies, regarding wind technology it became a subject of interest when first built wind plants came to the end of their lifetime, after 15 or 20 years of operation. For example, in [20], using technological learning for energy technologies predictions until 2080 are made, using different learning rates. Authors of [21] and [22] discuss learning curves in different energy technologies. The technological learning approach is applied to RES technologies development [23]. Multiple studies were conducted about progress ratios for wind farms [4], [24]. Learning curves were also used for energy policy support in different countries, for example, in the EU [25] and the US [23].

Regarding Austria, future wind potential has been studied in the literature [26], [27] and data about repowered wind parks can be found [28]. The potential and influence of repowering all Austrian wind plants are likely not examined. This work will try to examine this question and contribute to the determination of repowering potential in Austria. By this means, supporting the realization of the repowering process and the growth of wind energy usage.

3. Wind power in Austria

The first wind power plant in Austria was connected to the grid in 1994. Although it was considered that Austria does not have decent chances in wind power production, a great number of wind turbines were installed up till today. The current installed capacity in Austria is 3120 MW, saving around 3 million tons of CO_2 annually. Figure 3.1 shows the process of wind capacity growth from 1994 until 2021. Two key building phases can be seen: a first one from 2002 until 2006, and the second one after 2012, thanks to the Green Electricity Act (GEA). A few hundred million euros are expected to be invested in the wind energy sector in the upcoming year, supporting clean energy production [29]. The total wind capacity in Austria in 2030 is predicted to be around 7500 MW [27].

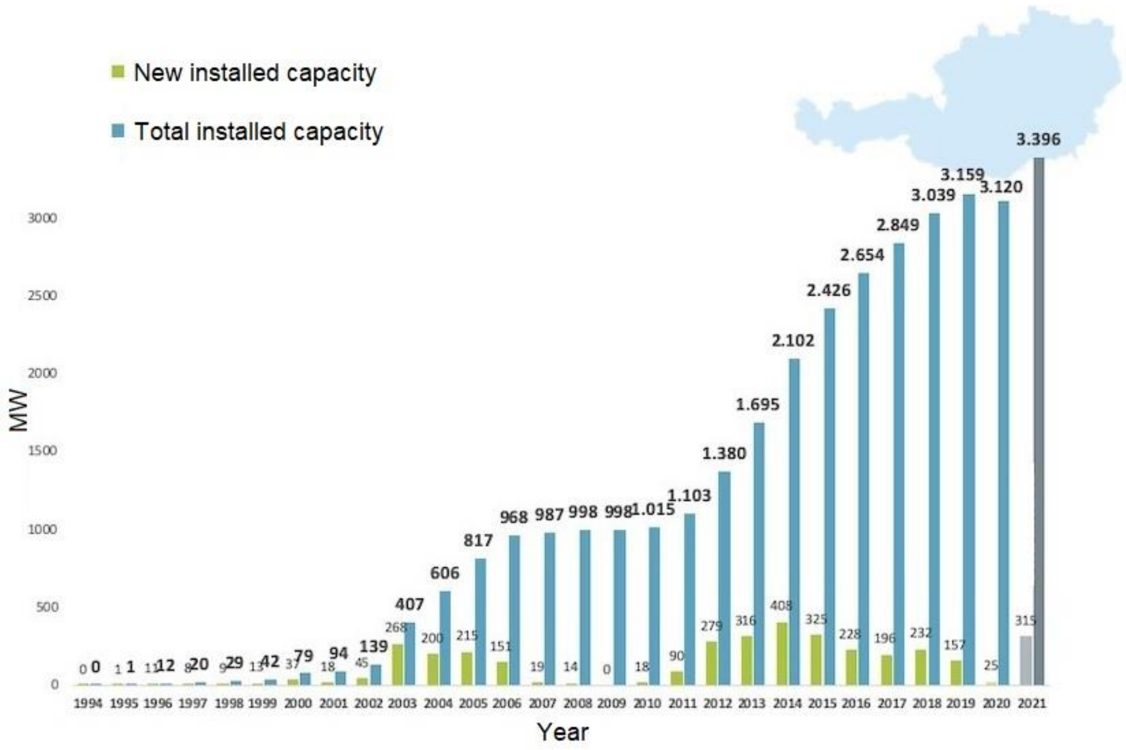

Figure 3.1 Wind capacity growth in Austria from 1995 until 2021 [6]

Development of the wind energy in Austria was strongly enhanced by Green Electricity Act from 2012 and by National Renewable Energy Action Plan (NREAP) [30]. Austrian national plans for 2030 and 2050 are determined by several incentives in Europe: Paris Agreement from 2015, package The Clean Energy for All Europeans, European Green Deal, and so on. By 2030 the EU's energy mix shall consist of at least 32% of RES, and by 2050 the EU shall obtain net-zero greenhouse gas emissions [31]. To reach aims by 2030, PV capacity is estimated to be 9,7 GW [32] and wind 7,5 GW [27].

Figure 3.2 is a map including almost all running wind parks in Austria. Mostly, the turbines have the capacity of 2 or 3 MW and are located in Burgenland or Lower Austria [33]. Lower Austria has 724 turbines within, which is around 1700 MW installed, and Burgenland has 437 turbines with a total power of 1104 MW. Other regions have a much lower, but not insignificant, number of turbines [34]. Many existing plants have great potential to be repowered in the future, owing to their favorable locations and profitability.

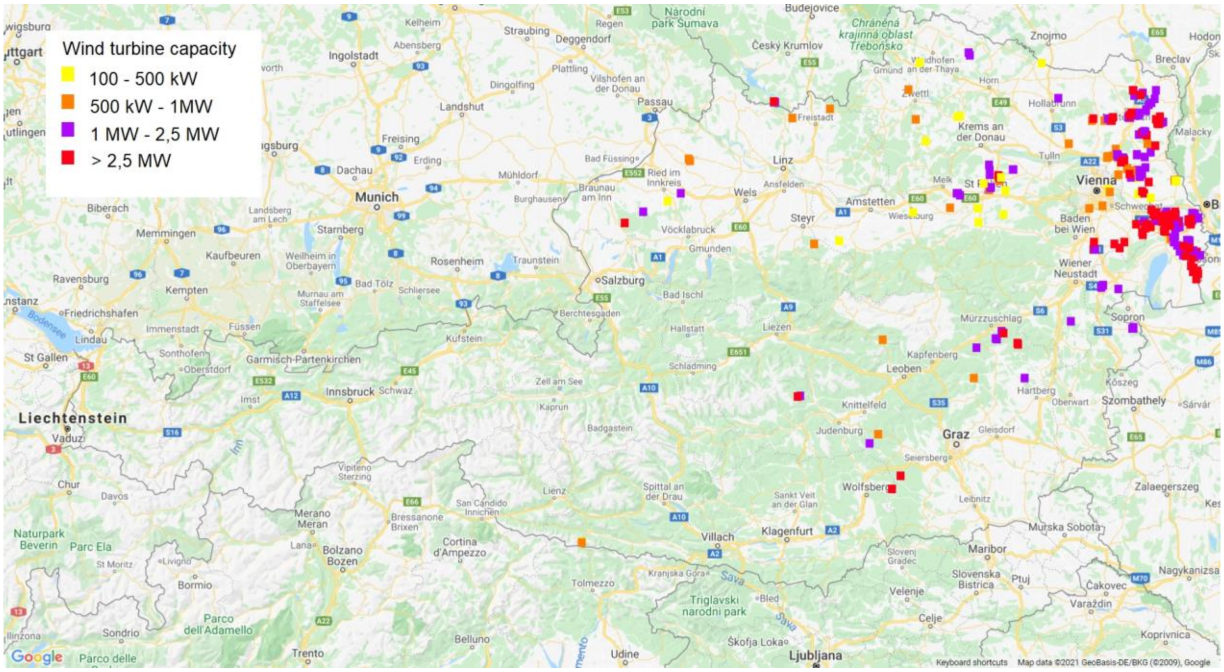

Figure 3.2 Map of wind parks in Austria [33]

The wind energy branch in Austria is consisting of manufacturers, suppliers, service providers, operators, and many other actors [35]. Figure 3.3 shows mostly used turbines, they are primarily supplied by Enercon and Vestas. About 60% of them are in private ownership and 40% in the ownership of utilities [30].

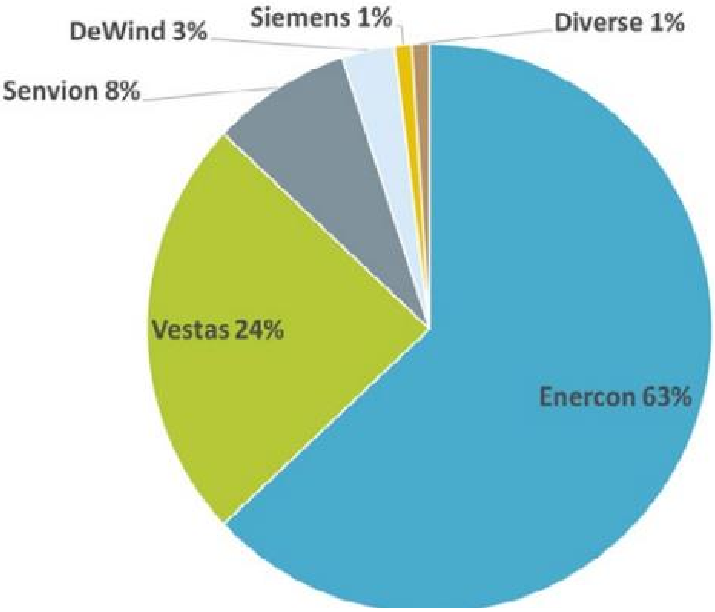

Figure 3.3 Manufacturers of Austrian wind turbines [30]

Total investment costs for wind parks in Austria are estimated to be around 1350-1570 EUR/kW, and O&M costs around 36-40 EUR/kW per year [30]. The price of electricity generated from the wind is determined by feed-in tariff (FIT). In case if the FIT is not defined for a certain year, the one from the previous year is used with a 1% decrease. The FIT is realized with the contract between the owner and the institution for selling and buying green energy in Austria (OeMAG). FIT contract lasts for 13 years, after that period, energy could be sold at a market price [34].

4. Repowering of wind power plants

Repowering of the wind farms is already a frequently used term, and it is defined as a process of replacing or improving old installations, which are coming close to the end of their lifetime, with the new ones. New modern turbines are more efficient and/or have a larger capacity [7], [13], [14], [36], [12].

Repowering is feasible due to the development of technology and technological learning for wind technologies. Figure 4.1 shows the development of wind turbines since the 1980s. A significant increment in the average installed power, height, and rotor diameter is noticeable [37].

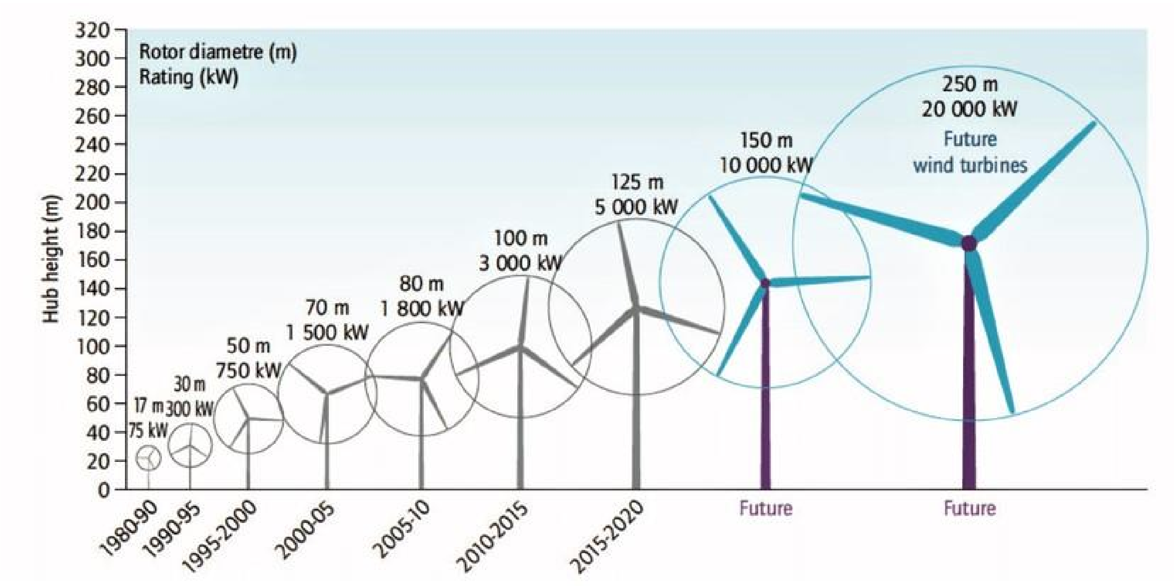

Figure 4.1 Development of wind technologies since 1980 [37]

4.1. Repowering modes

Repowering can be implemented in two main ways:

a. full repowering
b. partial repowering

Full repowering implies dismantling all the wind turbines and installing the new ones on the same wind farm. Partial repowering is replacing one or more components (e.g., generator), without changing the external layout of the farm [38]. The mode that is going to be applied, depends on the possible limitations, profitability, and owner's choice.

4.2. Benefits of repowering

Repowering brings multiple different benefits: ecological, economic, social, private. Due to the repowering, it is possible to generate much more energy with a smaller number of turbines. An increase of the hub height and rotor diameter, as well as lower start-up wind speeds of the turbine, enable the new wind park to produce much more energy than the old one [12]. Higher energy production directly increases the revenues for the producers. Furthermore, modern turbines are more reliable and require less maintenance [8]. Also, modern turbines have a lower impact on the environment. Because of their lower speed operation, they become more visually appealing and much quieter. Reduced number of turbines contributes to lower land occupancy [13]. New turbines are also much easier to connect to the grid [7], and they provide better support for the grid due to better power quality [13]. Repowering is made possible by the constant development of technology, and now it is also contributing to the advancement of the wind technology learning curves [13].

4.3. Repowering process drivers

There are few criteria with the most influence on repowering process of a specific plant [10]:

a. ENERGY PRODUCTION POTENTIAL

Annual energy production analysis decides how many and which turbine models are going to be used while repowering. Annual energy production will depend on the climatological conditions considering wind velocities and topographic variations, as well as turbine type and its power curve.

b. ECONOMIC ASPECTS

The economic aspect of repowering is important to determine the cost-effectiveness of the project. To calculate it, capital cost and electricity selling price need to be determined. Capital costs include initial investment in a new farm and as well as costs for decommissioning of the old plant. The electricity price will be influenced by the market price and the state policy deciding the different supporting tariffs or tradable green certificates. O&M costs also influence the economics of a project.

The payback period, internal rate of return (IRR), and profitability index (PI) are one of the values that are used for measuring economic success. The payback period is the time unit the initial investment is paid back. IRR shows the profitability of the project, it presents the rate when the net present value is equal to zero (equation 1). PI shows the connection between the costs and benefits of the project, it is calculated by dividing future cash flows by the capital costs.

c. ENVIRONMENTAL INFLUENCE

Repowering increases the share of renewables in the energy mix, thereby reducing greenhouse gas emissions. Reduction of the emissions shall encourage the installations of higher capacity. Repowering is also accountable for lower avian and visual impact.

d. SOCIAL APPROVAL

In addition to the safety ensured, the new power plant shall have a local acceptance. It is highly determined by the visual impact, but can be supported more by job creation and possible community funds.

e. TECHNOLOGICAL LIMITATIONS

An important decision in the project is regarding the time of construction and in which way is decommissioning handled. There are two main options: to keep the plant running while the new ones are constructed at the near location, or the construction comes after decommissioning at the same location [10]. New installations may require grid changes depending on the new capacity or other characteristics [8].

4.4. Evaluation of repowering project

Several parameters can be used in power plant repowering evaluation: capacity factor, net present value, full load hours, and levelized cost of energy [39].

Capacity factor

The capacity factor of the wind power plant is calculated with equation (1). It is the ratio of actual energy production and theoretical maximum production. It is a value between 0 and 1.

$$c.f. = \frac{E}{P * t} \tag{1}$$

$c.f. - capacity\ factor$

$E\ -\ actual\ energy\ production\ [MWh]$

$P -\ installed\ capacity\ [MW]$

$t - time\ period\ [h]$

Net present value (NPV)

NPV is discussed in detail in chapter 5.2.1. It represents today's values of the future cash flow. If NPV is equal to or larger than zero, the project has become profitable, and the initial costs are paid off.

Full load hours (FLH)

Parameter FLH represents the turbine's average annual production divided by the turbine's rated power. FLH is an indicator of how many hours a year a turbine could operate at full capacity. It is shown in equation (2).

$$FLH = \frac{E}{P} \tag{2}$$

$FLH - full\ load\ hours\ [h]$

$E - average\ annual\ production\ [MWh]$

$P - rated\ power\ of\ turbine\ [MW]$

Levelized cost of the energy (LCOE)

Equation (3) is the calculation of the levelized cost of the energy. LCOE represents the market price at which a wind plant needs to sell energy to pay off investment and operating costs during its lifetime.

$$LCOE = \frac{C + C_{o\&m}}{E_t} \tag{3}$$

$LCOE - levelized\ cost\ of\ the\ energy\ \left[\frac{EUR}{kWh}\right]$

$C - total\ investment\ costs\ [EUR]$

$C_{o\&m} - operation\ and\ maintaince\ costs\ during\ lifetime\ [EUR]$

$E_t - generated\ energy\ during\ lifetime\ [kWh]$

5. Methodology

In this chapter, the current situation of wind power plants in Austria is explained in detail and both analyzed data and assumptions are presented. The approach is described, as well as the used algorithm; how it works, and how it is used. Used equations are given and clarified. In the third part of this section, different scenarios are formulated describing repowering options. The optimization model is applied to each scenario. Assumptions, simplifications, and reasons why they are made are explained.

5.1. Data model

Model is made using data from open-source databases and publicly available literature. Given that, the examined data varies in some aspects comparing to the present-day Austria.

5.1.1. Wind power plants in Austria

Analyzed datasets, about the current situation of wind plants in Austria, are taken from the “Windrad-Landkarte” from the IG Windkraft website [33], shown in Figure 3.2. The total evaluated capacity of the wind park in Austria is 2804,475 MW. This includes 1224 wind turbines, with an average of 2 MW per turbine. The number is lower than the current installed capacity due to the lack of information about some wind parks. The average hub height is around 100 meters, and the average rotor blade diameter is about 80 meters.

Table 5.1 shows installed capacity per region in Austria. Most of the installed capacity is placed in Lower Austria or Burgenland, while Carinthia and Vienna have very low installed capacity. Lower Austria has more than 1500 MW of wind capacity installed, and Burgenland has more than 1000 MW. Lots of turbines in those regions have been installed before 2010, which opens a great opportunity for repowering in upcoming years. Since the current installed capacities are already large, the process of repowering has good chances to bring even better benefits. Styria and Upper Austria have lower installed capacities, which do not that work in favor of repowering. If there will be more new installed capacities in the future in those regions, repowering can be more profitable. Vienna has very low installed capacity, which is expected since it is an urban area. Carinthia has currently the lowest installed capacity, due to low wind potential and geographical obstacles in that area. It can be assumed that the main potential for repowering lays in the regions of Lower Austria and Burgenland.

Table 5.1 Installed capacity in Austria used in the model [33]

Region	Capacity [MW]
Lower Austria	1548,305
Burgenland	1007,7
Styria	194,15
Upper Austria	47,37
Vienna	5,65
Carinthia	1,3

5.1.2. Wind electricity prices

For the purchase of electrical energy from wind turbines, the feed-in tariff is used. The feed-in tariff is determined by the Green Electricity Act. The duration of the subsidy is 13 years. After that period, the wind plant operator can sell the electricity on the electricity market [40]. If no new regulation is issued, FIT from the previous year is used with a discount of 1% [34].

In the model, FIT from the Green Electricity Act from 2002 until 2021 is used for the first 13 years of the plant's lifetime. Before 2002 the constant price of 0,078 EUR/kWh was used, that is the assumption based on the FIT from 2002. This generalization is made because in the previous years the subsidies used to be determined locally per each region, and they are not known in detail. From 2021 until 2050 FIT is calculated based on the previous year with the 1% discount, since the future prices are still not known. Figure 5.1 illustrates the value of used FIT until 2050.

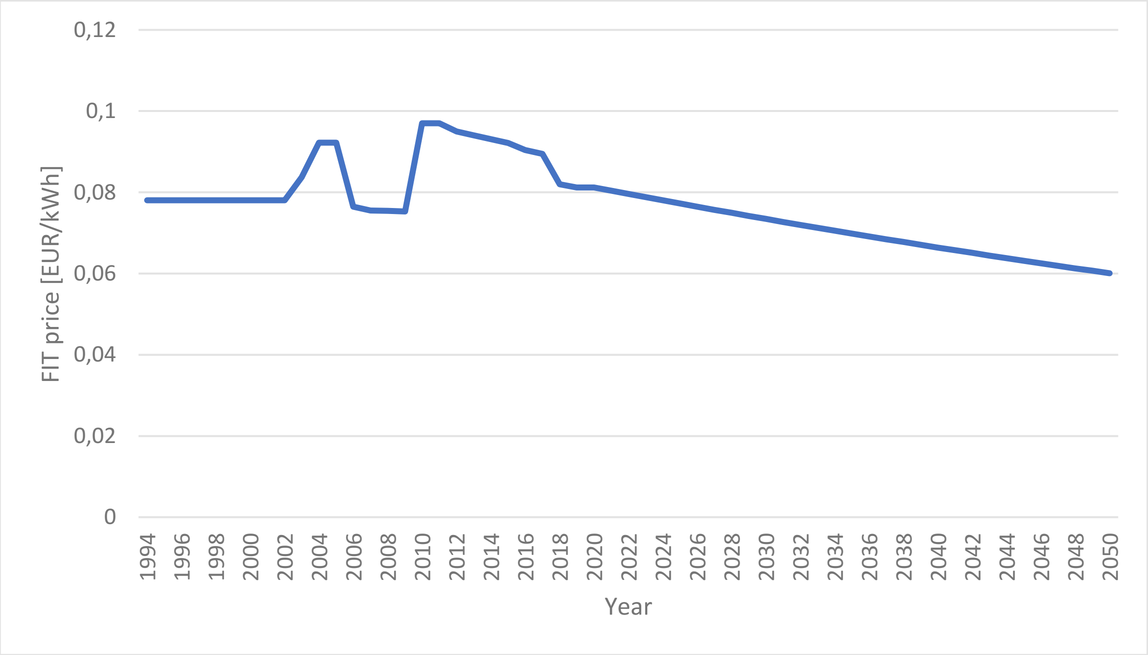

Figure 5.1 Wind energy market price for the first 13 years [34], [40]

When 13 years of the plant's lifetime has passed, produced energy is assumed to be sold at the energy market. It is sold by the day-ahead market price. The day-ahead market price is considered unique in each hour. Because of that, 8760 values are considered. In the model, hourly prices for the year 2017 are taken as representative values [41]. These prices are used in the model, regardless of which year it is. Because past day-ahead market prices are hard or impossible to access in open data format, this year is used as an assumption and simplification.

Figure 5.2 is a representation of the day-ahead prices for one day. The data for only one day is shown, to keep the simplicity of the figure. But a similar figure can be made for each day in a year. Each hour is specified with its price. It can be noticed that prices are in the range from 10 to 40 EUR/MWh.

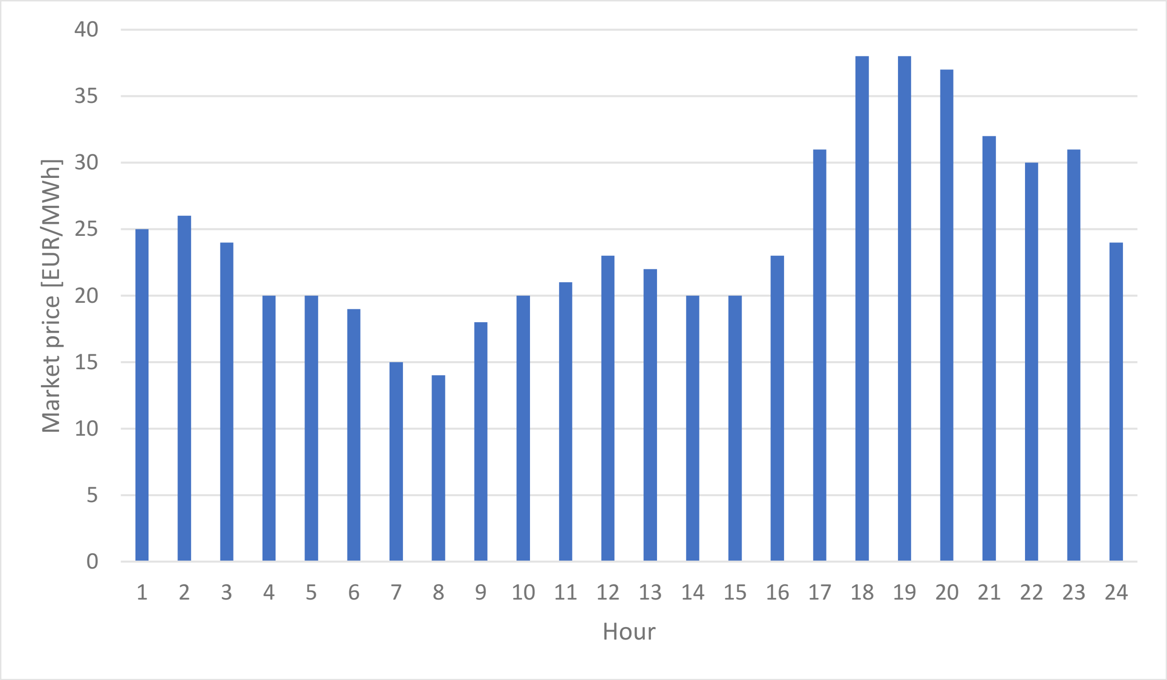

Figure 5.2 Wind energy day-ahead market price, used after 13 years (representation of one day prices) [41]

5.1.3. Generation from wind power plants

Generation data of the existing power plants is modeled by multiplying the capacity factor in each hour with the total capacity of the plant. It is calculated by using equation (1). Figure 5.3 represents the capacity factor of Austria for 24 hours. Data is from the year 2019, and it is generated for each hour in a year, with 8760 different values. Capacity factor values are in the range between 0 and 1. In case they are multiplied by 100, they are expressed as a percentage, from 0 to 100%. Data is taken from the platform "Renewables.ninja" which allows running simulations of the hourly capacity factor or energy output from wind and solar plants located anywhere in the world [42]. The platform offers accurate statistics regarding the specific location. Since this data is available only for 2019, all years are considered to have the same capacity factor profile, due to simplification.

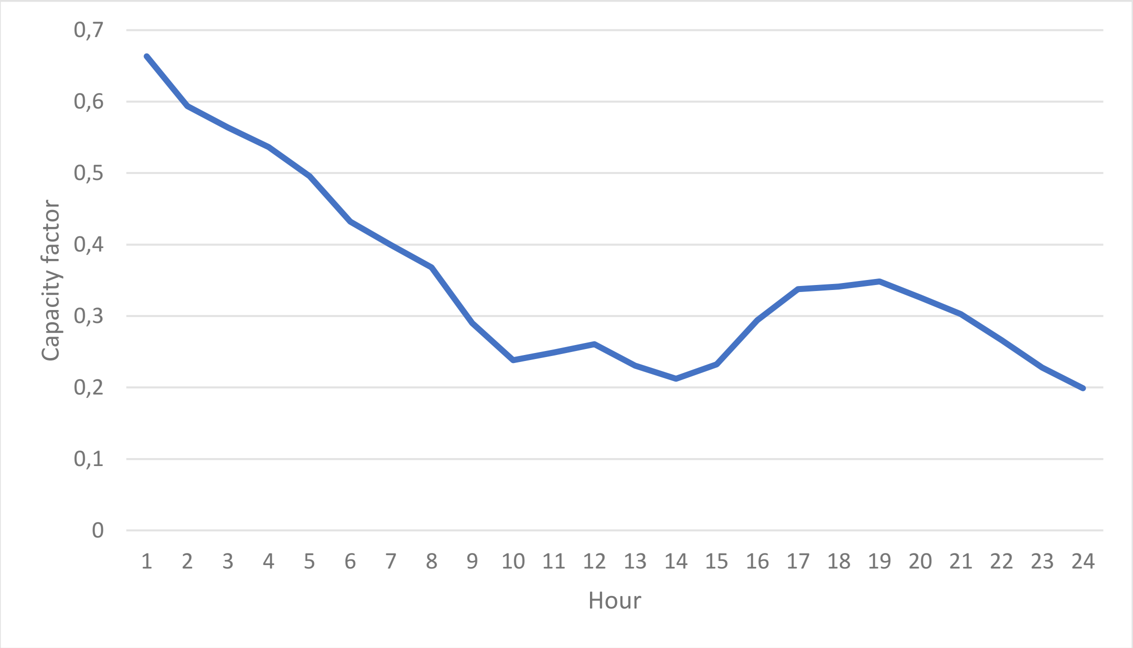

Figure 5.3 Wind capacity factor in Austria (representation of one-day capacity factor) [42]

5.1.4. Investment costs

Investment costs of the wind parks were changing significantly throughout the years. Figure 5.4 is showing this change in EUR/kW [43]. From 1995 until 2006 prices are taken from the data of wind turbines in Denmark and numerically scaled to the European market prices since there is a lack of price data for that period. There is a constant difference between prices in Denmark and Europe. That ratio is used to adapt Danish prices to European. After 2006, investment costs from the European market are considered [44]. Exact costs are not easy to determine, due to absence of the data from past periods. They vary from 1500 to 3000 EUR/kW.

Current investment costs for the new turbines in Austria are modeled to be in the range 1200-1700 EUR/kW [30]. Future costs are estimated by using technological learning, which is explained in the next chapter.

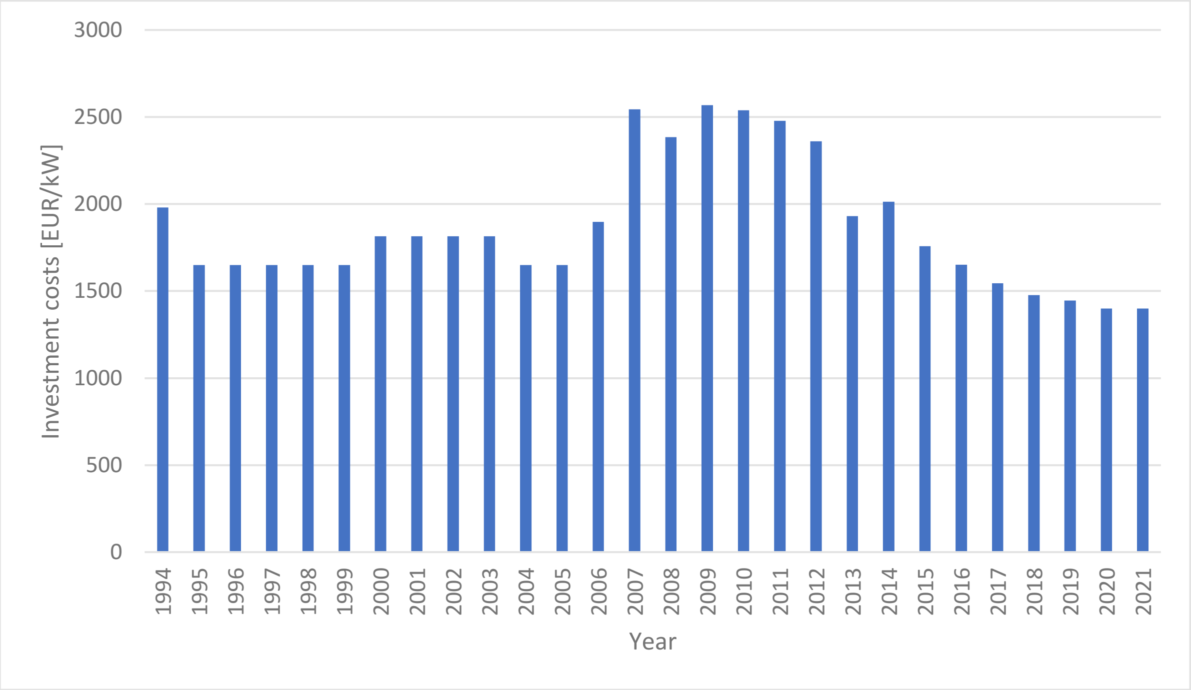

Figure 5.4 Investment costs for wind turbines in Europe [43], [44]

5.1.5. Operation and maintenance costs

Operation and maintenance, O&M, costs are calculated based on the investment costs. Older turbine's costs were calculated to be 3% of the initial costs, newer turbines had costs of 2% of initial costs, and the newest only 1% of initial costs due to the technology development. O&M costs are increasing with the turbine lifetime, and it is assumed that they will increase by 1% each year. Actual O&M costs of the projects are not widely known, but it is presumed that they drastically declined over the years [45]. O&M costs used in the model are shown in Figure 5.5. The average O&M costs are experiencing constant decline, which can be explained with the improvement of the wind equipment and upgrading the ways of maintaining.

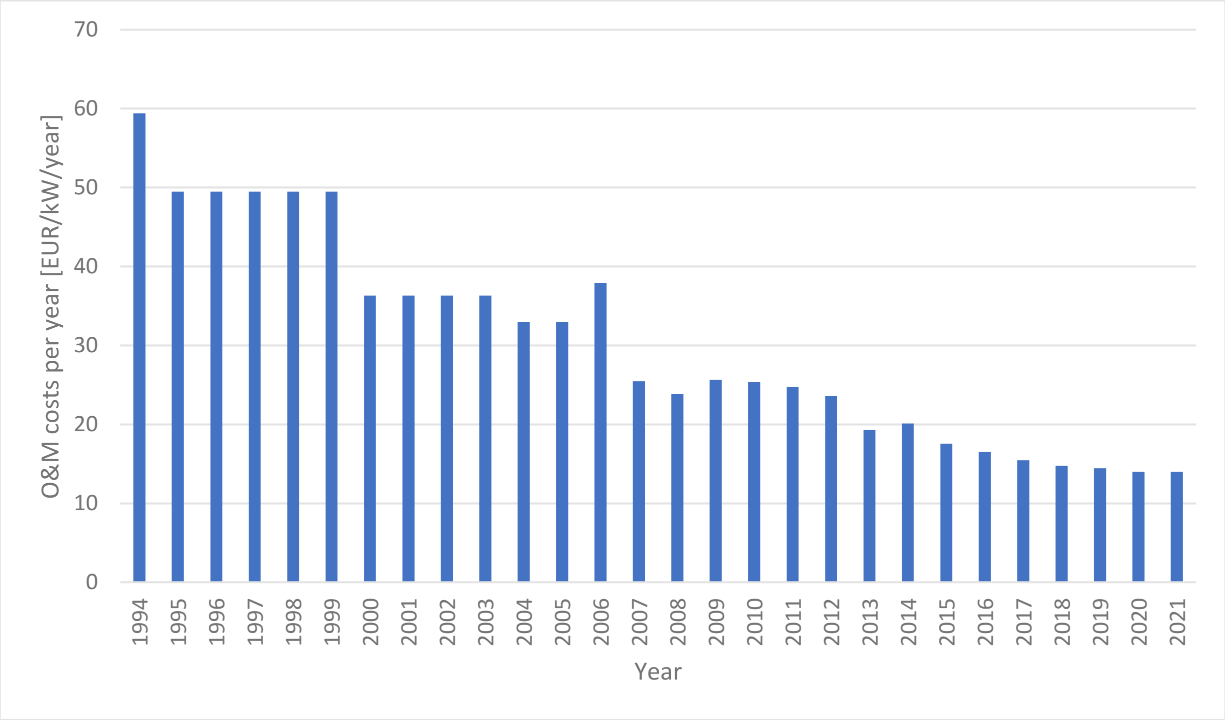

Figure 5.5 O&M costs for wind turbines in Europe [45]

5.1.6. Unit commitment data for curtailment forecast

The unit commitment model is based on the data downloaded from The Dispa-SET model[1] and adjusted to 2030 and 2050. The Dispa-SET is an open-source unit commitment and optimal dispatch model. It offers a free input database suitable to model the European grid, and it is used as the main source for the unit commitment model in this thesis. The unit commitment model is made to forecast possible energy curtailments due to wind energy growth by 2030 and 2050.

The total energy demand of Austria is taken for the year 2015 and increased by the rate of population increment for 2030 and 2050. Total load is divided by the population in 2015, and the obtained factor is multiplied by population in 2030 and 2050[2]. Figure 5.6 presents one of the 365 days on which is this presumption applied.

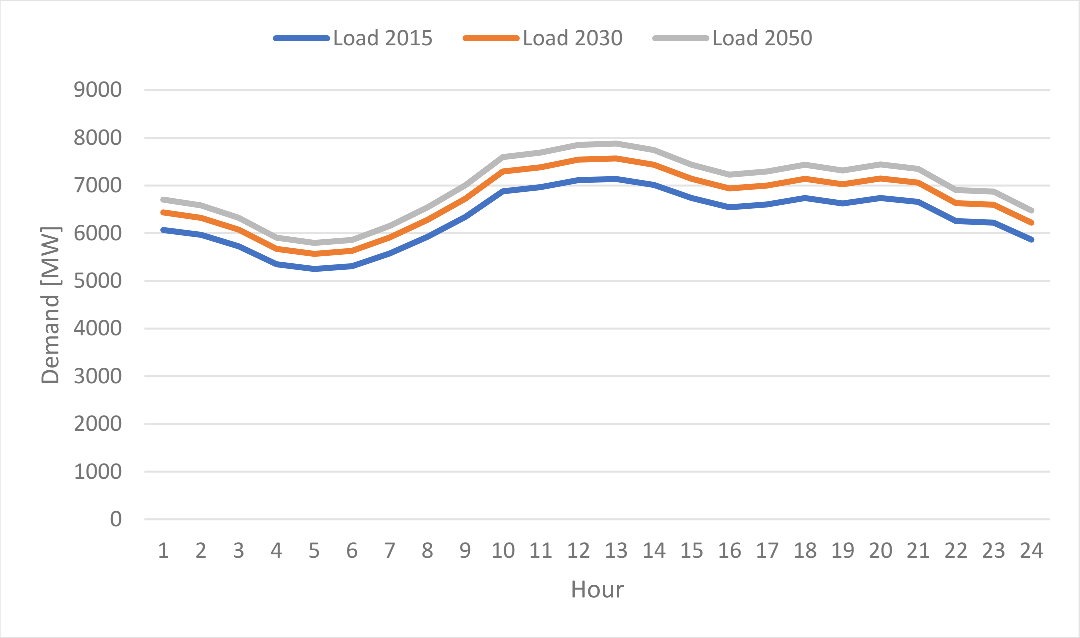

Figure 5.6 Demand for Austria in 2015, 2030 and 2050, shown for one day in a year

---

[1] http://www.dispaset.eu/

[2] https://www.austria.org/population

To run the unit commitment model, most of the installed capacities in Austria needed to be considered: oil plants, biomass plants (two different types modeled), and gas plants. Pumped hydro storage is described as a storage with a maximum 5936 MW charging power and charging efficiency of 80%. Table 5.2 shows data about mentioned plants that are used in the model. Maximum capacities and their efficiencies are listed. Coal is excluded from the model due to the predictions for 2030 and 2050 [35].

Table 5.2 Unit commitment model plants, with their capacities and efficiencies

Power plant	Maximum capacity [MW]	Efficiency [%]
Oil	288	41
Biomass 1	393	45
Biomass 2	290	46
Gas	6995	52,5
Pumped hydro	5936	80

Fuel prices, for previously mentioned plants, are approximated as an average of hourly prices from 2015, and they are shown in table 5.3. Real future price values are hard to predict. Prices are roughly approximated because they do not have a significant influence on the optimization outcome. They have a role in the decision of which plant is going to be started up first, which does not influence the final value of curtailment. The price of curtailment is set as the highest value, so the optimization will make curtailment a last resort, only if there is no other option.

Table 5.3 Unit commitment model fuel prices

Power plant	Fuel price [EUR/MWh]
Oil	38,25
Biomass	37,04
Gas	20,05

Wind data for the unit commitment model is calculated as described in chapter 5.2.6, by using obtained repowered capacities and wind capacity factors for Austria.

Generation from PV is determined by multiplying the solar capacity factor for Austria with the predicted rated power per hour in 2030 and 2050 [32], [42]. Capacity factor representation for one day in a year is shown in figure 5.7. A similar curve is used for all days in a year. One day is shown due to simplicity. In 2030, the total solar installed capacity in Austria is predicted to be 9,7 GW and in 2050, 26,7 GW. Following equation (1) production in each hour is estimated.

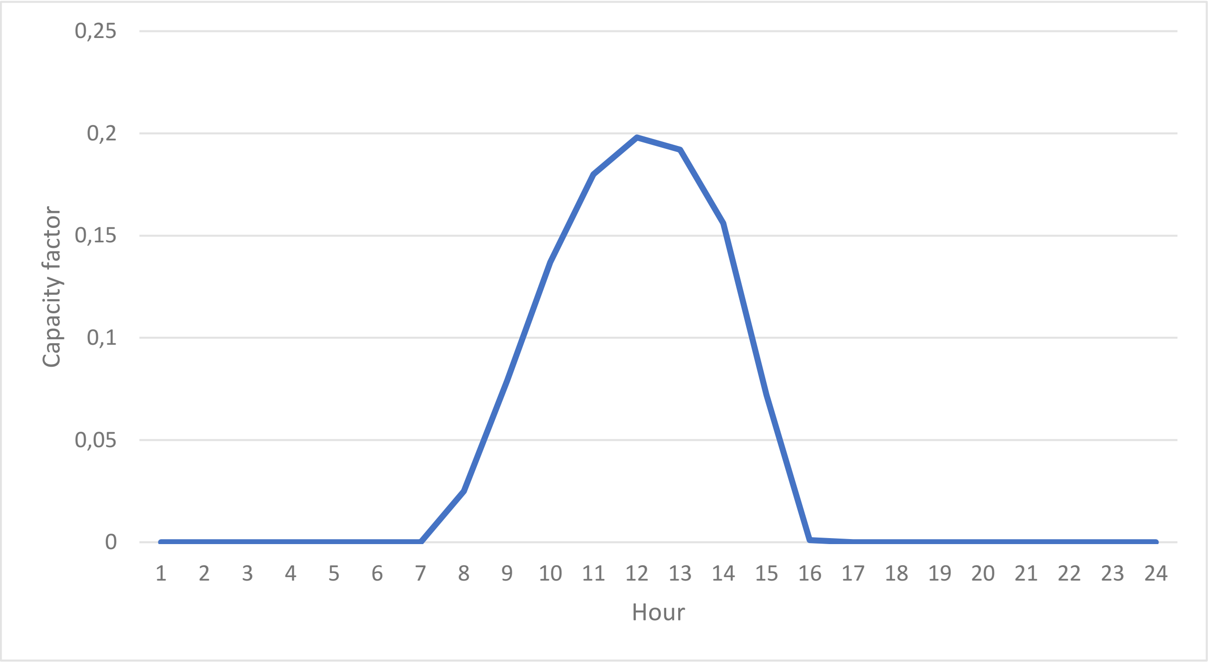

Figure 5.7 Wind capacity factor in Austria, representation of one-day capacity factor [42]

5.2. Calculations in the model

Further, explained, steps were calculated using the Python programming language[3] with the optimization solver Gurobi[4] in the PyCharm integrated development environment[5]. The most important codes are attached in the Appendix. Code 1 is determining repowering year for each park in Austria. Second code is an optimization for determining repowered park capacity and the number of turbines. Last code is a unit commitment model for curtailment approximation.

5.2.1. Calculating timing for repowering

Wind turbines are designed to operate for 20 or 25 years. Repowering of the wind turbines can take place somewhere in that period or even sooner, usually not before 10 years of operating. But if the O&M costs get too high or efficiency gets too low, repowering is required prior to its 20 years of operation. Repowering is considered possible after at least 10 years of its operation, since it is highly unlikely that it will happen before. The main constraint in the model is shown in equations (4), (5), and (6). It is representing the net present value of the existing turbine that is going to be repowered. NPV represents today's values of the future cash flow [39]. NPV should be zero or larger than zero, which means that the previous investment costs and additional costs are paid off. The discount rate of wind technologies is usually estimated to be 2,7% [46]. The change of the discount rate does not make any significant difference in the timing of the repowering. That is why it is fixed value and not considered in the sensitivity analysis.

---

[3] https://www.python.org/

[4] https://www.gurobi.com/

[5] https://www.jetbrains.com/pycharm/

$$NPV = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i} - \sum_{i=1}^{n} C_{o\&m_i} - C_o \tag{4}$$

With the variables:

$NPV - net\ present\ value\ [EUR]$

$C_i - \ total\ cash\ flow\ of\ the\ wind\ park\ in\ year\ i\ [EUR]$

$C_{o\&m_i} - operation\ and\ maintenance\ costs\ in\ year\ i, increasing\ 1\%\ annually\ [EUR]$

$C_o - initial\ capital\ costs\ of\ a\ wind\ park\ [EUR]$

$n\ - a\ lifetime\ of\ a\ wind\ park\ [year]$

$r - discount\ rate\ for\ wind\ technology\ [\%]$

$$C_i = \sum_{t=0}^{8760} C_t * E_t \tag{5}$$

Where:

$C_t - \ price\ of\ the\ wind\ energy\ in\ hour\ t, FIT\ or\ market\ price\ \left[\frac{EUR}{kWh}\right]$

$E_t - \ production\ of\ the\ wind\ park\ in\ hour\ t\ [kWh]$

$$E_t = cf_t * P \tag{6}$$

Where:

$cf_t - capacity\ factor\ in\ Austria\ in\ hour\ t$

$P\ -\ wind\ park\ rated\ power\ [kW]$

If the wind park is still younger than 20 years, for the following years O&M costs and possible costs due to the loss of efficiency are controlled. It will be profitable to repower the plant if these costs, shown with equations (7) and (8), get too high (lower than income). As already mentioned, O&M costs are assumed to be increasing by 1% annually. O&M costs are likely to grow exponentially, but the linear approximation is used for the first 20 years. With the lifetime efficiency of the wind power plants tend to fall. Efficiency is expected to reduce around 1,6% per year [47]. The repowering moment is defined with the first part of the equation (7).

$$Ci \leq C_{loss} = C_{\eta_{loss}} + C_{o\&m} \tag{7}$$

Where:

C_{loss} $-$ $total\ cash\ loss\ due\ to\ efficiency\ reduction\ and\ O\&M\ costs\ [EUR]$

$C_{\eta_{loss}}$ $-$ $cash\ loss\ due\ to\ efficiency\ decrement\ [EUR]$

$C_{o\&m}$ $-$ $total\ O\&M\ costs\ [EUR]$

$$C_{\eta_{loss}} = \sum_{t=0}^{8760} E_t * C_t * (1 - (1 - \eta_{loss} * n)) \tag{8}$$

Where:

η_{loss} $-$ $annual\ efficiency\ reduction\ [\%/100]$

n $-$ $a\ lifetime\ of\ a\ wind\ park\ [year]$

5.2.2. Repowering process and constraints

Once repowering is possible, the following constraints in equations (9), (10), (11), and (12) need to be considered. The number of newly installed turbines is equal to or lower than the number of the old turbines. This assumption is made because the capacity of each existing hub will be higher, so it is unlikely that the number will increase. The new park's capacity is assumed to be at least slightly higher than the previous one, even though it is usually much higher after repowering. Since it is not known whether current wind parks have the possibility of a bigger area occupation, there are some constrains added to it. Equation (12) ensures that the occupied area stays the same, meeting the 4 diameters distance requirement between turbines [9]. The total capacity of the repowered park is calculated by multiplying the capacity of the one turbine with the total number of new turbines. This value is calculated by optimizing mentioned constraints to maximizing the capacity of the repowered park, shown in equation (13).

$$n_{new_i} \leq n_{old_i} \tag{9}$$

$$P_{new_i} \geq P_{old_i} \tag{10}$$

$$P_{new_i} = P_{turbine_i} * n_{new_i} \tag{11}$$

$$4d_{new_i} n_{new_i} \leq 4d_{old_i} n_{old_i} \tag{12}$$

$$\max_i P_{new_i} \tag{13}$$

n_{new_i} – number of turbines in a repowered wind park

n_{old_i} – number of turbines in a park before repowering

P_{new_i} – total capacity of the repowered park $[MW]$

P_{old_i} – total capacity of the park before repowering $[MW]$

$P_{turbine_i}$ – capacity of a turbine which is possible to use while repowering $[MW]$

5.2.3. Calculation of the future installed capacity

Two main values concerning each park are year of repowering and new capacity. For each existing park, new repowered capacity is determined by considering the optimistic and pessimistic situation. In the optimistic case, the highest total capacity of the park is considered for repowering, and in the pessimistic, the lowest capacity. The capacity of a new park is calculated considering repowering options explained in chapter 5.3. Total wind capacity in a certain year is calculated by summing all capacities existing at that moment. That means that parks that are repowered until that year are contributing to the total summation with new capacity, which can either be an optimistic or pessimistic option. Parks that are not repowered until analyzed year are added in summation with their old capacity.

5.2.4. Prediction of total installed wind capacity in Austria

This chapter is added to compare the total capacity due to repowering and possible total wind capacity in Austria in 2030 and 2050. Total installed capacity in Austria is predicted following the rising trend of the data from 2010 until 2021. It is predicted by using linear regression from the Python class sklearn.linear_model.LinearRegression [48]. Even though the rise of RES is connected to exponential growth, it could be approximated linearly because it is approximated at the small section which is growing linearly. The process of this calculation can be found in chapter Appendix, in Code 3.

5.2.5. Calculation of the future investment and operation and maintenance costs

Future investment and operation and maintenance costs are calculated by using one-factor technological learning mechanisms described with equations (14) and (15). The learning rate (LR) for wind technologies is a value between 16-32 % [49]. The decrement is calculated based only on the increment of capacity due to the repowering. Accumulation of the wind capacity should have an influence on the technology growth and thus trigger a fall in costs of wind technologies.

$$C_t = C_o * \left(\frac{P_t}{P_o}\right)^{-a} \tag{14}$$

$$\frac{LR}{100} = 1 - 2^{-a} \tag{15}$$

Where:

$C_t -$ investment cost in year t $[EUR/kW]$

$C_o -$ initial investment costs $[EUR/kW]$

$P_t -$ installed capacity until year t $[MW]$

$P_o -$ initial installed capacity $[MW]$

$LR -$ learning rate $[\%]$

$a -$ learning by doing factor

5.2.6. Flow diagram representation of the used algorithm

Figure 5.7 represents the idea of an algorithm used to calculate the moment of repowering and to estimate important parameters of repowered wind farms. All previously explained steps and equations are included. Input data is described in chapter 5.1. Codes used for these calculations can be found in chapter Appendix as Code 1 and Code 2.

Furthermore, lifetime, lt, is checked. The first check, if the park is older than 25 years, decides straight repowering of the plant. Also, repowering is possible only after 10 years of its lifetime. If the plant has not reached 10 years, it is checked again for the following year. One of the main constraints for repowering is positive NPV. That means that the existing power plant and its expanses financially paid off. It is calculated as stated in equation (4). When NPV becomes positive, the park can be considered for repowering.

If the park's NPV is positive, and it is over 20 years, the plant is ready for repowering. Repowering can happen before the plant reach 20 years in case the price of losses gets bigger than income. To be exact, when the condition of the equation (7) has been met. Examined losses are losses of income due to decrement of efficiency and increment of O&M costs. These requirements are checked again for the next year until the exact date of repowering is determined, and then optimization for capacity calculations (last part of flow diagram) can start. Repowering optimization is conducted by fulfilling the constraints from chapter 5.2.2 and considering different turbines mentioned in chapter 5.3.

This same algorithm is applied to every one of all wind plants in the model. Decided output data for each plant is predicted year of repowering and possible capacity. For the new capacity of the plant, two cases are brought, the one when the capacity is maximum (optimistic) and one when the capacity is minimum (pessimistic).

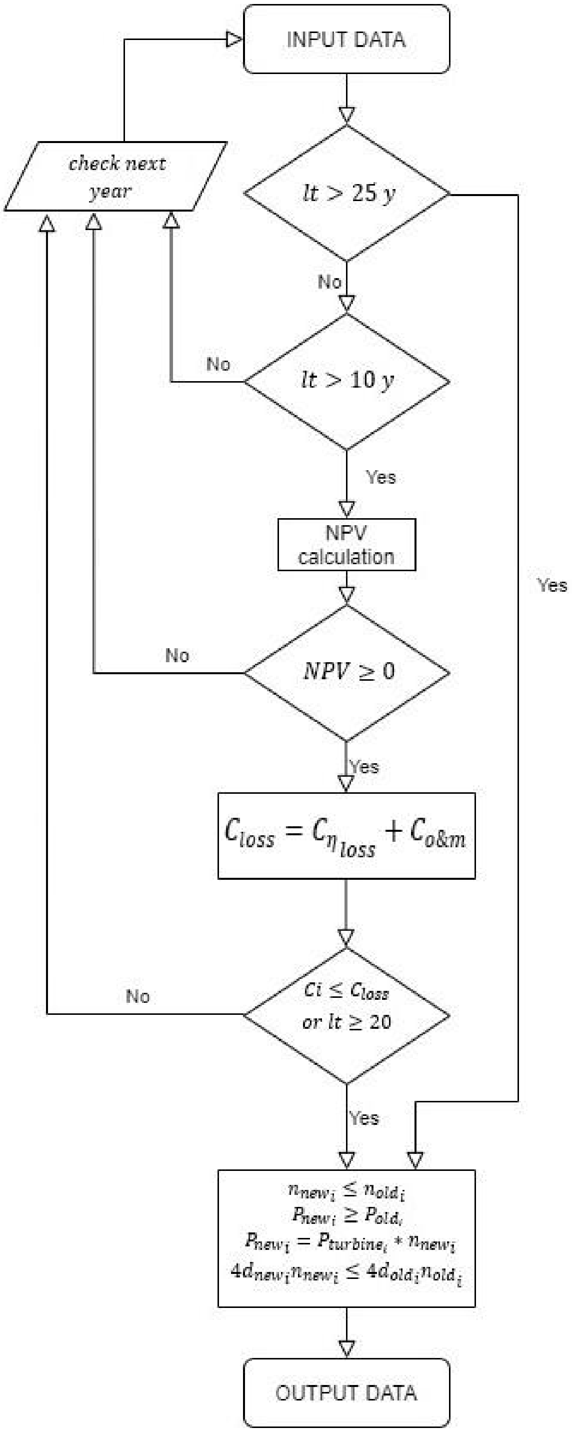

Figure 5.8 Optimization algorithm represented with the flow diagram

5.2.7. Determination of energy production and curtailment

To roughly approximate possible wind energy production in 2030 and 2050 obtained capacities need to be multiplied with the wind capacity factor of Austria, as stated in equation (1). Obtained results are compared to the current annual production of about 7 TWh [29].

Due to the increase of energy coming from renewables in the energy mix, energy curtailment may occur for several hours in a year. To determine that the unit commitment (UC) model is made for 2030 and 2050. Used data is explained in chapter 5.1.6. Power plants that are included in the model are gas plants, oil plants, biomass plants, hydro, solar, and wind. Classic plants are determined by their rated power, minimal load working power, efficiency, and fuel price. Other constraints, like ramp-up or -down capacities and times, are eliminated to achieve simplicity. For RES, energy generation is considered as hourly values for 2030 and 2050. The following equations (15) – (17) give further explanation of this model. Equation (15) is a balance between production and demand in each of 8760 hours. Production is listed on the left side and demand on the right side of the equation. The energy produced by a certain plant is established by the plant's capacity and efficiency. Pumped hydro is modeled as storage, clarified with equation (16). The state of charge of the reservoir is equal to the state in the previous hour, increased by charged energy and decreased by discharged energy. Hydro run-of-river are excluded from the model because their energy is considered free, so they will make extra curtailment that could not be distinguished from wind curtailment. This assumption has no impact on the outcome because wind curtailment is not directly connected to run-of-river plant generation. The main optimization function is minimizing energy price, equation (17). Photovoltaic and wind production is precisely set for each hour, since their prices are equal to zero. Activation of other power plants is determined with price order. Plants with lower fuel prices will be the first to produce. To optimize the model, the price of the curtailment is set as the highest price in the model. So, curtailment will be the last option in optimization. Curtailment determination code is available in chapter Appendix as Code 4.

$$E_{pv}(t) + E_{oil}(t) + E_{gas}(t) + E_{bio}(t) - E_{ch}(t) + E_{dis}(t) + E_{w}(t) - E_{c}(t) = d(t) \tag{15}$$

$$SoC(t) = SoC(t-1) + E_{ch}(t) * \eta - E_{dis}(t)/\eta \tag{16}$$

$$\min_{i} \sum_{t=1}^{8760} E_i(t) * p_i(t) \tag{17}$$

E_{pv} – PV energy production [MWh]

E_{oil} – production from oil power plants [MWh]

E_{gas} – production from gas power plants [MWh]

E_{bio} – production from biomass power plants [MWh}

E_{ch} – energy for charging hydro reservoir [MWh]

E_{dis} – energy for discharging hydro reservoir [MWh]

SoC – state of charge of hydro reservoir [MWh]

η – hydro reservoir charging efficiency [%/100]

E_w – wind energy production [MWh]

E_c – energy curtailment [MWh]

d – total energy demand of Austria in 2030 or 2050 [MWh]

t – time in hours [h]

E_i – production of power plant i [MWh]

p_i – price of fuel for power plant i [EUR/MWh]

5.3. Scenarios - repowering options per region

Different repowering scenarios are possible due to the multiple-choice of new turbines. When repowering, three different turbines on two different heights is considered as an option. Possible capacities are selected depending on the wind park region; for example, in Vienna, lower capacities are chosen because it is unlikely that the higher ones will be installed in an urban area. Each turbine is characterized by capacity, hub height, diameter, and full load hours. Full load hours are calculated, following the equation (2), based on installed capacity and energy prediction [42].

5.3.1. Carinthia

In table 5.2 wind turbines considered for repowering in Carinthia are shown. Since there is a few turbines installed and low capacity in that region, lower capacities are taken into consideration. Another reason is that the region has a lower wind potential and environmental barriers. The first turbines listed, Vestas, have lower capacity but a higher number of FLH, then Repower and Enercon with higher capacity. This event can happen because of the turbine quality, but it is not directly considered in the model.

Table 5.4 Turbine options for repowering in Carinthia [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Vestas V100	1.8	120	100	1893
		150		2176
Repower MM82	2	120	82	1270
		150		1484
Enercon E101	3	120	101	1368
		150		1592

5.3.2. Upper Austria

In table 5.3 wind turbines considered for repowering in Upper Austria are shown. Upper Austria has a larger number of turbines installed compared to Carinthia and wind potential is higher. That is why larger capacities are taken into the account.

Table 5.5 Turbine options for repowering in Upper Austria [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Vestas V112	3.3	120	112	2304
		150		2537
Enercon E112	4.5	120	112	1844
		150		2047
Enercon E101	7	120	126	1632
		150		1817

5.3.3. Styria

In table 5.4 wind turbines considered for repowering in Styria are shown. Styria has greater capacity options because of its higher wind potential.

Table 5.6 Turbine options for repowering in Styria [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Enercon E112	4.5	120	112	1808
		150		2086
Enercon E126	7	120	126	1602
		150		1858
Vestas V164	8	120	164	1999
		150		2302

5.3.4. Vienna

In table 5.5 wind turbines considered for repowering in Vienna are shown. Possible repowering capacities are relatively low because of the urban area and considering existing plants.

Table 5.7 Turbine options for repowering in Vienna [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Vestas V66	1.65	120	66	2509
		150		2684
Vestas V66	2	120	66	2266
		150		2433
Enercon E92	2.35	120	92	3076
		150		3267

5.3.5. Burgenland

In table 5.6 wind turbines considered for repowering in Burgenland are shown. Possible repowering options in this region are high because of its great wind potential.

Table 5.8 Turbine options for repowering in Burgenland [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Vestas V66	1.65	120	66	2509
		150		2684
Vestas V66	2	120	66	2266
		150		2433
Enercon E92	2.35	120	92	3076
		150		3267

5.3.6. Lower Austria

In table 5.7, wind turbines, considered for repowering in Lower Austria, are shown. Lower Austria has great wind potential. Most of the installed turbines in Austria are placed somewhere in that area. Those are the reasons why turbines with high capacity and FLH are being considered as a repowering option.

Table 5.9 Turbine options for repowering in Lower Austria [42]

Turbine	Capacity [MW]	Hub height [m]	Diameter [m]	FLH [h]
Repower 6M	6	120	126	2649
		150		2823
Enercon E126	7.5	120	126	2415
		150		2577
Vestas V164	9.5	120	164	2846
		150		3024

6. Results

In this chapter, results obtained with model and optimization are shown and explained. Calculations and data used, are explained in the previous chapter. The main estimated values are the year of repowering for each park, the maximal and minimal obtained capacity of the park, total capacity in Austria due to repowering, possible energy production, and curtailments. Based on the results, sensitivity analysis is made, varying certain parameters.

6.1. Timing for repowering

The timing of repowering is determined for each wind park in Austria individually. It is calculated as explained in chapter 5.2.1 and with figure 5.8. NPV, lifetime, money losses, and incomes are parameters determining the year of repowering for every park. For all parks in the model, repowering is calculated to happen between 17 and 27 years.

Table 6.1 shows how many plants are likely to be repowered after a particular lifetime. For example, 15 parks are estimated to be repowered after 17 years of operation, 22 parks after 18 years, 26 parks after 19 years, 143 parks after 20 years, and so on. Most of the plants should be repowered after 20 years. Such results have been awaited, given the expected lifespan of wind farms. The expected lifespan of wind plants is from 20 until 25 years, which is perfect timing for repowering.

Table 6.1 Number of parks planned to be repowered in a particular lifetime

Lifetime [years]	17	18	19	20	21	22	23	24	25	26	27
Parks repowered	15	22	26	143	21	14	6	7	17	1	2

Table 6.2 shows how many parks can be repowered starting from a specific year and what total maximal capacity can be reached due to repowering. Lots of parks are possible to be repowered this year, since most of them are at the end of their lifetime. Some of those power plants could have been repowered even earlier. The actual situation will certainly differ, depending on the appeared barriers. Barriers can be diverse, such as political conditions, financial and personal possibilities of the owner, relief interference, and similar. The latest repowering of existing plants takes place in 2040. In that year, the last currently existing power plants will come to the end of their lifespan. Probably, after 2040 there will be even more plants repowered because in meantime new plants will be built. Those unknown possibilities are not taken into consideration in this model. Even though they can be significant potential, they are too unpredictable to be included.

The last line of the table presents possible capacity in listed years, for an optimistic option of repowering, repowering of all power plants to the maximum capacity. The increase in total installed capacity in Austria is shown. The values include repowered and old capacity in a specific year. More details about these values are stated in chapter 6.3. While comparing initial potentials from 2021 and potentials in 2040, capacity almost doubled in less than 20 years. And compared to the starting value of around 2800 MW, more than 4000 MW in 2030 and more than 6000 MW in 2050, obtained with repowering is significant improvement.

Table 6.2 Numbers of parks possible to repower in a certain year, and possible total installed capacity due to repowering

Year	2021	2025	2026	2028	2029	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Number of parks repowered	98	29	10	2	5	20	14	17	23	17	14	10	8	6	1
Possible capacity [MW]	3830	4132	4288	4314	4353	4683	4827	5140	5444	5694	5898	6050	6169	6234	6238

6.2. Repowering scenarios – optimistic and pessimistic case

Meeting the requirements from chapter 5.3.2 and considering repowering options per region from chapter 5.3, each park is determined two repowering possibilities: optimistic (maximal repowering capacity) and pessimistic (minimal repowering capacity).

Since it is too complex to show outcomes for each plant, table 6.3 shows one plant per region chosen as an example. Each plant is described with the location, depending on the region the wind turbines from chapter 5.3 are chosen as repowering possibility. Other things that are connected to each park are the year of commissioning, calculated year of repowering, old capacity, new possible capacities, turbine types, old and new diameters, and the total number of turbines in the park. For example, plant Zurndorf V in Burgenland built in the year 2014 is decided to be repowered in 2034, after a 20-year lifetime. The old capacity of 6 MW, obtained with 2 turbines, is repowered with one 9,5 MW turbine in the optimistic scenario or with one 6 MW turbine in the pessimistic scenario. So, two turbines are replaced with only one turbine, not extending the already used area. The total repowering capacity could be even larger if an additional area for the park is available. Chosen turbines and their diameters are presented in the table. As an example, in the park Schrick VI repowering is happening after 19 years of lifetime, due to the high costs for O&M and efficiency losses, the equation (7) condition is met. The table shows that much larger capacities with a lower number of turbines can be installed while repowering. The same parameters, which are shown in the table, are estimated for all existing power plants considered in the model. After the estimation for all parks is completed, further information, like total capacity, energy, and curtailment, can be computed.

Table 6.3 Examples of park repowering data in different regions

Power plant	Plöckenpass II	Munderfing	Moschkogel	Unterlaa	Zurndorf V	Schrick VI (Teil 1)
Region	Carinthia	Upper Austria	Styria	Vienna	Burgenland	Lower Austria
Built [year]	2017	2014	2006	2005	2014	2012
Repowered [year]	2037	2034	2026	2025	2034	2031
Old capacity [MW]	0,8	15	11,5	4	6	4,6
New capacity - optimistic [MW]	3	28	16	6	9,5	9,5
New capacity - pessimistic [MW]	1,8	16,5	13,5	4,7	6	6
Old turbine	Enercon, E53	Vestas, V112	Enercon, E70/E4	Siemens, Bonus	Enercon, E101	Enercon, E82
New turbine - optimistic	Enercon, E101	Enercon, E126	Vestas, V164	Vestas, V66	Vestas, V164	Vestas, V164
New turbine - pessimistic	Vestas, V100	Vestas, V112	Enercon, E112	Enercon, E92	Repower 6M	Repower 6M
Old diameter [m]	53	112	71	54	101	82
New diameter - optimistic [m]	101	126	164	66	164	164
New diameter - pessimistic [m]	100	112	112	92	126	126
Old number of turbines	1	5	5	4	2	2
New number of turbines - optimistic	1	4	2	3	1	1
New number of turbines - pessimistic	1	5	3	2	1	1

6.3. Total capacity due to repowering

Total capacity in a particular year is calculated by alternating existing capacity with new repowering in a certain year. If the existing plant is not repowered yet, the old capacity is added to the sum. If the existing plant is repowered until that year, it is added to the sum with new capacity. Figure 6.1 presents the total installed wind capacity through the years until 2050. The year 2020 shows an initial capacity of around 2800 MW. The consequence of repowering can be seen in the rise of capacity compared to the initial year, 2020. The optimistic scenario is a case when each park is repowered to the maximum possible capacity. It is shown as blue columns in the figure. The pessimistic when the minimum capacity is chosen for repowering, and it is represented with the red color. In the year 2030, the total capacity is between 3500 MW and 4500 MW. That means that the repowering process has contributed to a rise of around 1000 or 2000 MW. This does not include newly installed wind capacities, which can make an additional contribution. In the year 2050, the total wind capacity is in the range of 4500 MW to 6300 MW. Reasons for this wide range are unpredictable decisions in repowering. For example, it is not known does the owner want to increase capacity slightly or a lot, that is the reason why optimistic and pessimistic cases are considered.

It is noticeable that after 2040 there is no new repowering scheduled. Capacities are calculated only by offering the options mentioned in chapter 6.3, and it is possible that much larger capacities can be obtained. Larger capacities can also be obtained by installing new capacity in Austria from 2021 until 2050. With this consideration, more repowering can be expected after 2040 or even sooner.

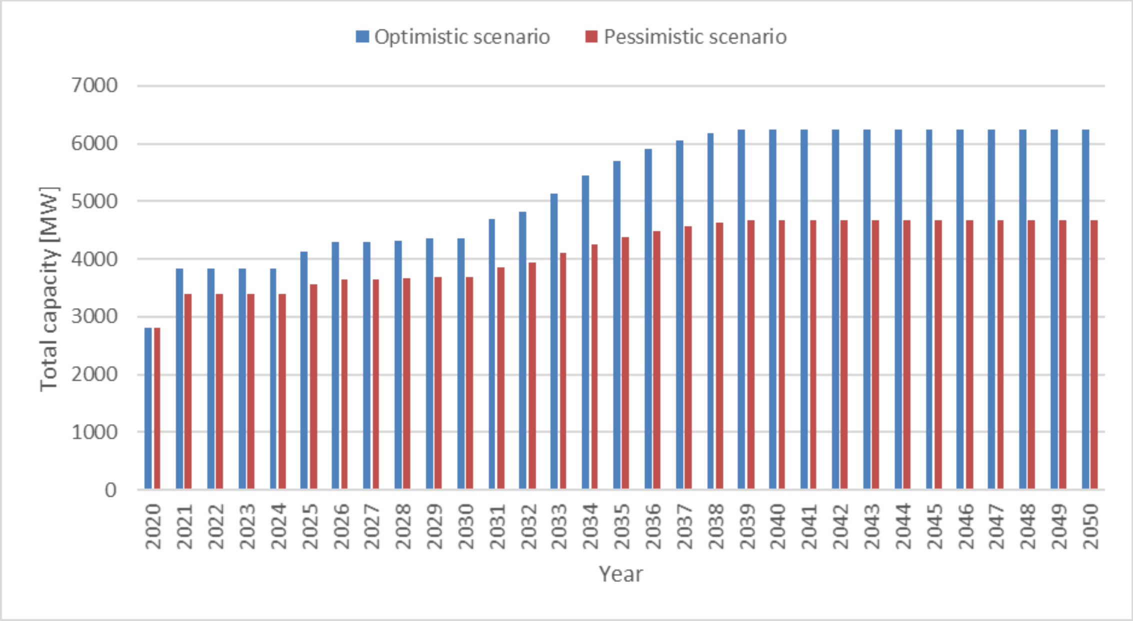

Figure 6.1 Growth of capacity due to repowering through years

In table 6.4 total capacities until years 2030 and 2050 for both scenarios are presented. The optimistic scenario, in which maximal possible capacities in the model are chosen for each power plant, provides more favorable results: capacity of about 5353 MW for 2030 and 6238 MW for 2050 just by repowering. In a pessimistic scenario, chosen capacities for repowering either stayed the same as before or are slightly increased, so results are not so pleasing: 3681 MW for 2030 and 4668 MW for 2050. The reason why larger capacities are not obtained is due to the condition of not occupying bigger surfaces, while repowering and newly built installations after 2021 are not considered.

Table 6.4 State of wind capacity in Austria due to repowering in 2030 and 2050

Year	Capacity - optimistic [MW]	Capacity – pessimistic [MW]
2030	4353,67	3681,27
2050	6238,09	4668,59

Table 6.5 represents the possible increment in capacities per region in Austria by the year 2050. Maximal capacity is modeled as an optimistic case and minimal possible capacity as a pessimistic one. The highest repowering potentials are in Burgenland and Lower Austria, where most of today's turbines are installed. Capacity in Lower Austria is almost 4000 MW in optimistic and 3000 MW in pessimistic case. Both values are higher than the initial state not only of Lower Austria but of whole Austria as well. As predicted, Lower Austria is the region with the highest wind repowering potentials. Just as well, Burgenland has great potentials in upcoming years. It can reach around 2000 MW for the optimistic and pessimistic cases. In the other regions, where the repowering potential is much lower, the differences between the optimistic and pessimistic are not significant. Lowest expected installed capacities are in Carinthia and Vienna. These results were already assumed in the methodology section. By installing additional capacity in the future in these regions, higher repowering potential can be obtained.

Table 6.5 Possible state of wind capacity per region in Austria due to repowering until 2050

Region	Capacity - optimistic [MW]	Capacity - pessimistic [MW]
Carinthia	6	3,6
Upper Austria	105	58
Styria	353	256
Vienna	13	10
Burgenland	2124	1623
Lower Austria	3637	2718

6.3.1. Repowered capacity comparison to total expected capacity

This section is added to compare the growing trend of wind capacity in Austria to predicted capacities obtained with repowering. The difference between those values gives the size of capacity that would have to be additionally installed or repowered to keep the growing trend of wind capacity in Austria. As explained in chapter 5.2.4 future total wind capacity in Austria is predicted by applying linear regression on data from 2010 till today.

The linear approximation is shown in figure 6.2. The detailed process of figure creation is mentioned in the chapter Appendix in Code 3. This calculation can be used to make a comparison between total expected capacity (which is the sum of repowered capacity and newly built capacity in the future), and capacity achieved with repowering. Results correspond to the existing predictions for 2030, even though they are slightly lower [27]. Based on the given figure, the estimated capacity for the year 2030 is 5673 MW, and for 2050 is 10288 MW. Comparing to the estimated repowered capacity difference for 2030 is 1319 MW for optimistic and 1992 MW for the pessimistic case. That means that about 1500 MW should be either installed additionally or while repowering a larger area. This way, it could probably reach predicted wind capacities. Regarding the year 2050, the difference is much bigger; it is 4050 MW for optimistic and 5619 MW for the pessimistic scenario. Lots of new wind plants are likely to be put into operation until the year 2050, so the difference will be covered. Moreover, there are high chances that there will be more repowering after the year 2040. But this can only be predicted and decided in the future once new plants are installed with the latest technological improvements. Comparing the estimation shown in the figure and estimation for repowering, repowering contributes to the growth and supports the capacity-rising trend.

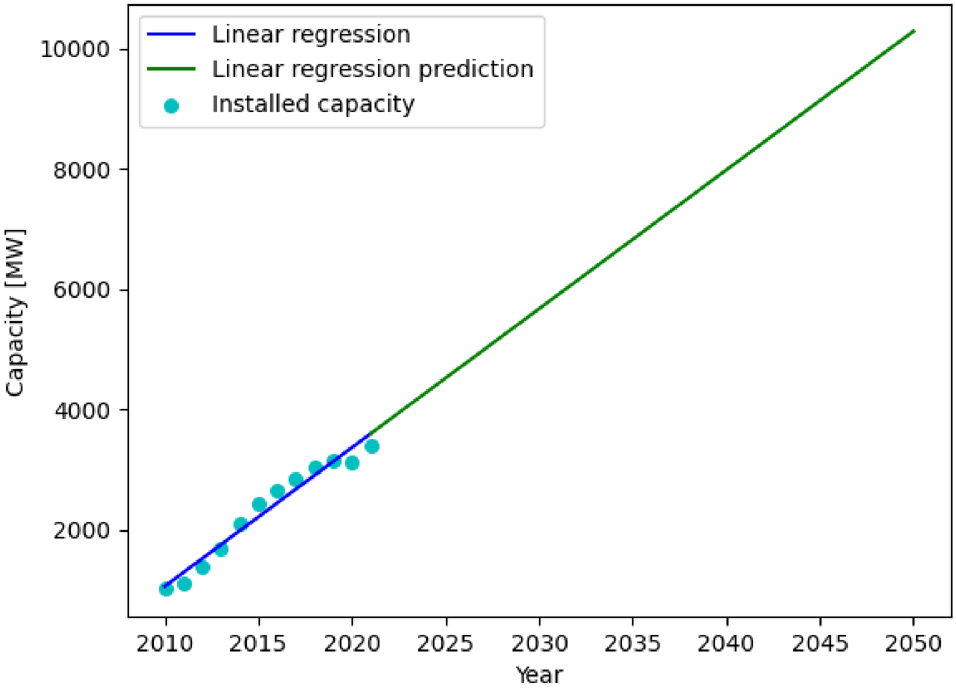

Figure 6.2 Linear regression of the installed capacity in Austria until 2050

6.4. Cost's decrement due to technological learning and repowering process

Based on the equations given in chapter 5.2.5 and costs of wind parks in Austria presented in chapter 3 future costs can be estimated. Figure 6.3 presents investment costs and O&M costs decrement until 2050 due to the technological learning and capacity increment, for both optimistic and pessimistic scenarios. The learning rate used in the calculation presented with the picture is 16%. In the technological learning equation, equation (14), initial values of capacity and initial costs are considered. For this figure that is the investment cost of 1200 EUR/kW, and O&M costs of 36 EUR/kW per year. Estimated capacities values due to repowering are also taken into the equation, to obtain solutions.

Predicted investment costs for 2030 are 1074 EUR/kW for the optimistic case and 1121 EUR/kW for the pessimistic case, and in 2050 they are 981 for the optimistic case and 1056 for the pessimistic case. Possible O&M costs for 2030 are 32 EUR/kW per year for the optimistic and 33,6 EUR/kW per year for the pessimistic case, and in 2050 they are 29 EUR/kW per year for the optimistic and 32 EUR/kW per year for the pessimistic case.

Optimistic case, as assumed, gives better results, by having a stronger impact on costs decrement. Some changes between the years in the figure are sharp, even they might not be in a real case. It is due to the rapid growth of capacity potential in some years. The figure shows that after 2040 there is no further decrement because in the model there are no new parks repowered after that year. Otherwise, the curve will have a further fall, but it can be predicted when the new wind capacities are installed.

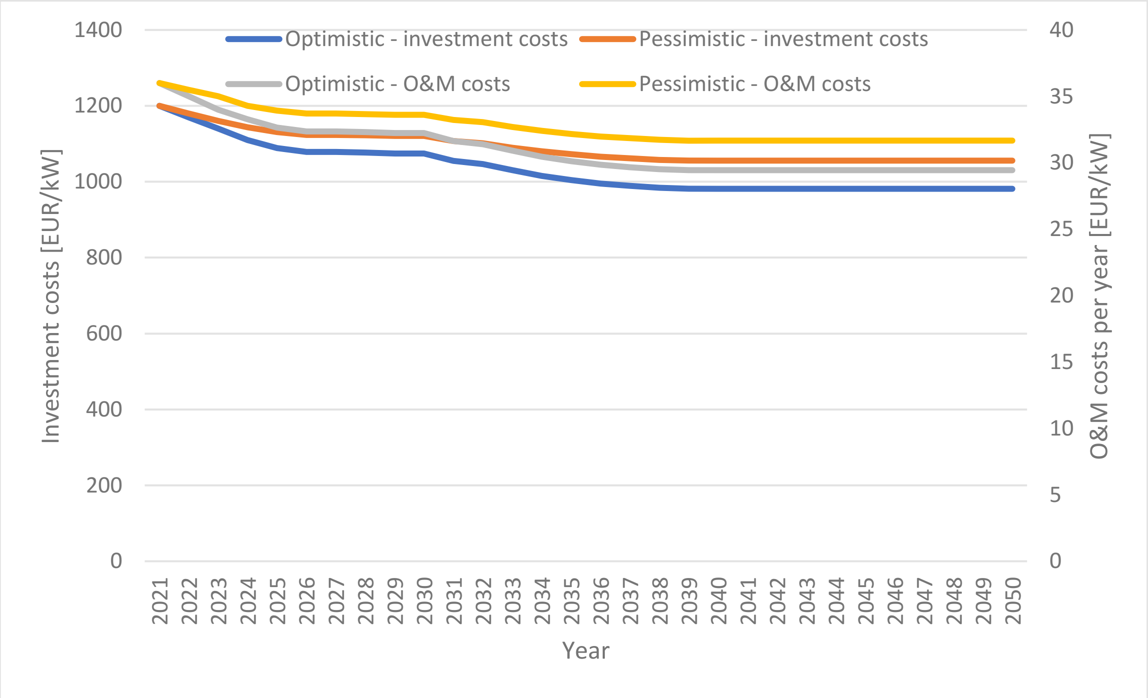

Figure 6.3 Decrement of investment costs due to technological learning

6.5. Annual energy potential and possible curtailment

Using the clarification from the first part of chapter 5.2.7 total annual energy production is roughly calculated based on the capacity factor and capacities shown in chapter 6.3. To calculate annual energy production in 2030 and 2050, equation (1) is used, with previously obtained results. The wind capacity factor of Austria is multiplied in each hour by the obtained capacities. Production in each hour for 8760 values is calculated. By summating those values, further results are achieved.

Table 6.6 is showing the estimated annual energy for 2030 and 2050 for optimistic and pessimistic cases, as well as the annual generation in 2020 [29]. A significant increment in energy production is evident in all cases by comparing it to 7 TWh generation in 2020. The increment is larger in the optimistic case as expected, while in that case installed capacity is bigger. In 2030, the optimistic generation is around 10 TWh annually, and in 2050, it is almost 9 TWh annually. That is around 2 or 3 TWh increment for 10 years difference. In 2050, the difference between optimistic and pessimistic cases is larger due to higher uncertainties. In an optimistic case, it is around 15 TWh, and in a pessimistic case, it is around 11 TWh. Values did not increase that much 20 years from 2030. There should be considered that energy production in 2050 stayed the same since 2040, due to the lack of the future data about wind plants in Austria.

Table 6.6 Total annual wind energy generation in Austria in 2020, 2030 and 2050

Year	Energy - optimistic [MWh]	Energy – pessimistic [MWh]
2020	7000000	
2030	10348061	8748556
2050	14823348	11096715

Based on the approach and data from chapter 5.2.7, the UC model is simulated. Wind energy production is represented by hourly values. It is calculated from capacity factor and capacities from table 6.4. By applying the minimization equation, equation (17), and setting the highest price (penalty price) for energy curtailment, annual curtailments are determined.

Possible predicted curtailments on an annual basis are shown in table 6.7. By comparing 2030 and 2050, in optimistic cases curtailments doubled in those 20 years, and in pessimistic cases, they do not grow so drastically. Curtailments in 2030 are around 143 GWh annually for optimistic and around 100 GWh for the pessimistic case. In 2050, curtailments are almost 300 GWh in optimistic and almost 130 GWh in pessimistic cases. Curtailments in 2050 are similar to those in 2040 because no new repowering is scheduled in that period for now. Curtailment in all cases is around 1% of total energy production. In 2030, for the optimistic case it is 1,38% of total energy production, and 1,13% for the pessimistic case. In 2050, it is 1,93% for optimistic and 1,14% of total annual generation for the pessimistic case. For pessimistic cases, when less capacity is installed, total annual curtailment is lower. Even though it seems that the pessimistic case is giving more favorable results, if there is an option for export of energy curtailment, the optimistic case gains additional value. More precise curtailment values can only be predicted when those years come.

Table 6.7 Total annual curtailment of wind energy generation in Austria due to repowering in 2030 and 2050

Year	Curtailment - optimistic [MWh]	Curtailment – pessimistic [MWh]
2030	143107	98802
2050	285938	126960

Figure 6.4 represents one day in Austria in 2030, with predicted total energy production and consumption. It is obtained with the UC model, described in chapters 5.1.6 and 5.2.7, and with Code 4 from Appendix chapter. Although the analysis was carried out on an annual basis, only one day is presented to make details more visible. The energy situation is given per hour of the chosen day. Generation include production from all Austrian plants included in the UC model. Demand presents total load of Austria in 2030 in the given day. The production follows nicely the consumption curve. But it can be noticed that generation in eleventh, twelfth, thirteenth, fourteenth, and fifteenth exceeds the demand. In those hours, a curtailment due to wind production occurs. Curtailments occur because of the top high-pitched production from wind power plants, which cannot be controlled. That is not a daily case, curtailment only happens in very few hours in a year. Previously shown, annual curtailments (in table 6.7) are being calculated by summing up the existing curtailments in each hour in the whole year.

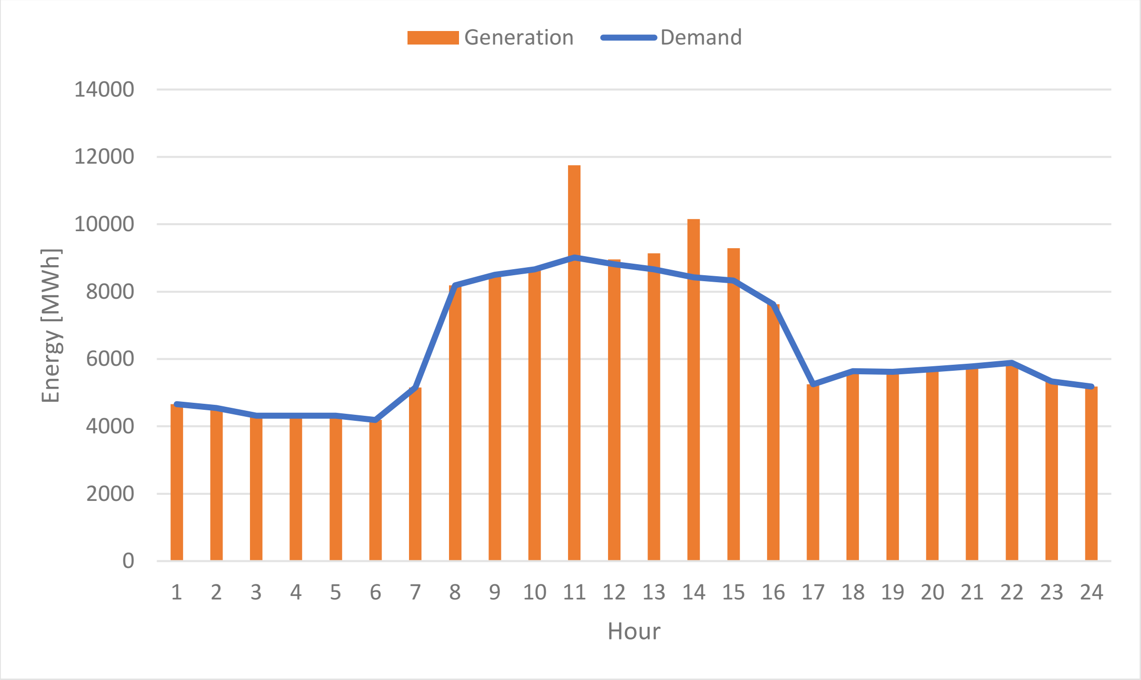

Figure 6.4 Total generation and consumption of energy in Austria, representation of one day in 2030

6.6. Sensitivity analysis

Sensitivity analysis is made by varying certain parameters and the impact on the model is examined. Observed parameters are learning rate in the technological learning equation, initial investment, and O&M costs in Austria in 2021, and hub heights of repowered plants. Learning rates vary from 16-32%, so few different options are chosen. Initial investment costs are estimated to be in the range from 1200 until 1700 EUR/kW, and O&M costs 36-40 EUR/kW per year. Two different hub heights are examined: one on 120 meters and the other on 150 meters. It is hard to predict future hub height because of the unknown relief and obstacles, so just two options are chosen for simplicity.

6.6.1. Investment and operation and maintenance costs

Table 6.8 presents sensitivity analysis for future investment costs in 2030 and 2050. Varied parameters are learning rate and initial capital costs. The learning rate is set to be 16% in one case, 20% in the other, and 30% in the last variation. Initial capital cost is considered to be 1200 EUR/kW for the first, 1500 EUR/kW for the second, and 1700 EUR/kW for the third case. It can be noticed that the costs are dropping faster for higher learning rates. An optimistic scenario, the one with the higher capacity accumulated, gives lower prices, as assumed. Just as well, prices in 2030 are lower than in 2050, since there is more capacity to be accumulated until the year 2050. Future investment costs in 2030 are predicted to be in the range from 956 till 1521 for the optimistic, and in the range from 1043 till 1587 for the pessimistic case. Investment costs in 2050 are calculated to be in the range from 795 till 1390 for the optimistic, and in the range from 923 till 1495 for the pessimistic case. All cases and variations give satisfactory outcomes.

Table 6.8 Future investment costs for 2030 and 2050 – sensitivity analysis

Initial cost		1200 EUR/kW		1500 EUR/kW		1700 EUR/kW	
Scenario	LR	2030	2050	2030	2050	2030	2050
Optimistic	16	1074	981	1342	1226	1521	1390
	20	1041	927	1301	1159	1475	1314
	30	956	795	1196	994	1355	1126
Pessimistic	16	1120	1055	1400	1319	1587	1495
	20	1099	1018	1374	1273	1557	1442
	30	1043	923	1304	1153	1477	1307

Figure 6.5 is a graphical representation of the variation between different learning rates in optimistic and pessimistic cases. It shows the case with initial capital costs of 1200 EUR/kW. Different learning rates are taken into the account. The figure is made for the learning rates of 16%, 20%, and 30%, and for both optimistic and pessimistic cases. Considering mentioned, the figure shows the six different technological learning curves for investment costs.

As mentioned before, a higher learning rate and optimistic scenario are showing better results: lower costs. The best performance is shown with the light blue line. That line is made for an optimistic case and a learning rate of 30%. A higher learning rate always gives better results than the lower one, not depending on the case. That line is connected to the highest rise of capacities through the years. All cases mark a drop in costs, which is expected. Depending on the learning rate and amount of capacity installed, the curve will have different steep. Starting value is 1200 EUR/kW. End investment costs values are in the range from 800 until 1100 EUR/kW, which can be considered as a significant fall regarding this kind of technology. Costs vary in a wide range due to unpredictability.

Again, it is evident that there are no positive results, costs decrement, between 2040 and 2050. This problem has been clarified before. But that period offers new possibilities for further improvements and costs decrements.

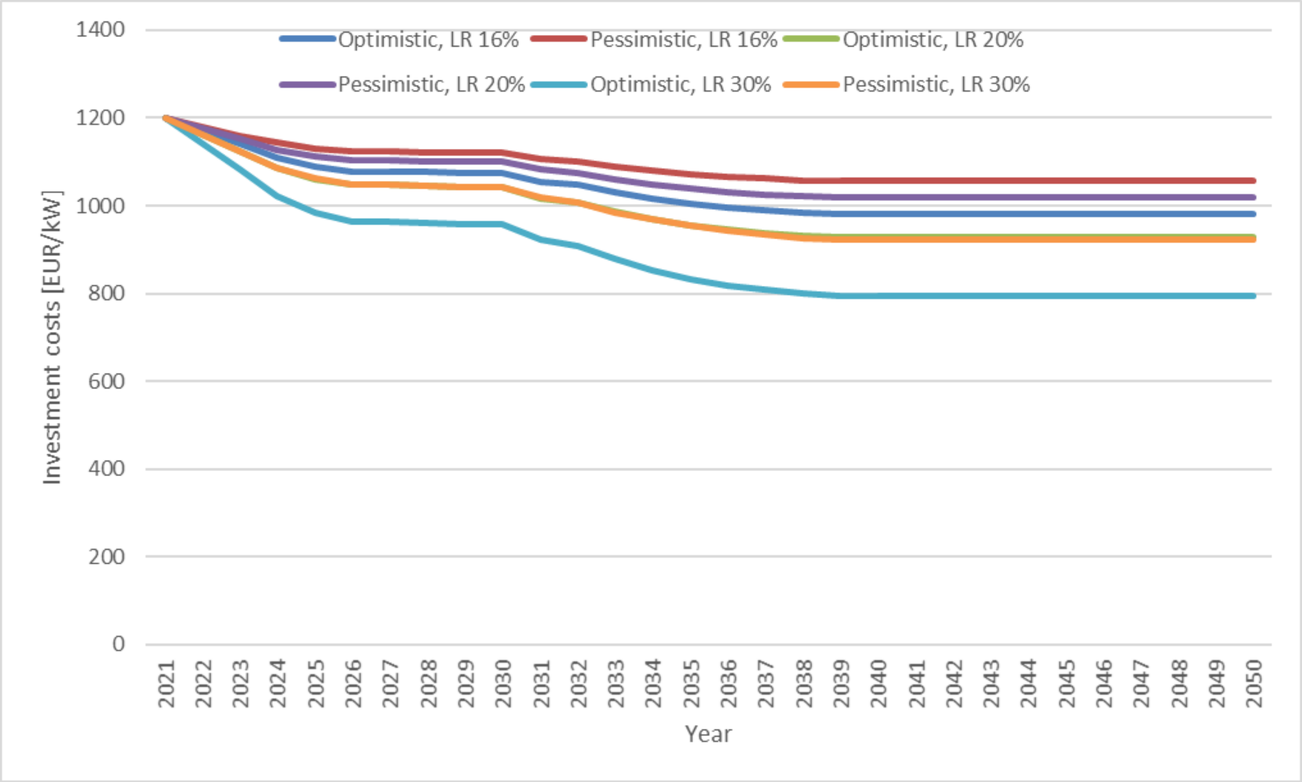

Figure 6.5 Future investment costs – LR sensitivity analysis

Table 6.9 presents sensitivity analysis for future O&M costs in 2030 and 2050. Varied parameters are learning rate and initial O&M costs. The learning rate is set to be 16% in one case, 20% in the other, and 30% in the last variation. Initial O&M cost is considered to be 36 EUR/kW per year for the first, 1500 EUR/kW per year for the second, and 1700 EUR/kW per year for the third case. It can be noticed that the costs are dropping faster for higher learning rates. Prices in the optimistic scenario are lower than in the pessimistic ones, because of higher installed capacity. Just as well, prices in 2030 are lower than in 2050, since there will be more capacity installed in 2050. Future O&M costs in 2030 are predicted to be in the range from 28 till 35 for the optimistic, and in the range from 31 till 37 for the pessimistic case. O&M costs in 2050 are calculated to be in the range from 23 till 32 for the optimistic, and in the range from 27 till 35 for the pessimistic case. All cases and variations give the decrement compared to the initial costs.

Table 6.9 Future O&M costs for 2030 and 2050 – sensitivity analysis

Initial O&M costs		36 EUR/kW per year		38 EUR/kW per year		40 EUR/kW per year	
Scenario	LR	2030	2050	2030	2050	2030	2050
Optimistic	16	32	29	34	31	35	32
	20	31	27	32	29	34	30
	30	28	23	30	25	31	26
Pessimistic	16	33	31	35	33	37	35
	20	32	30	34	32	36	33
	30	31	27	33	29	34	30

Figure 6.6 is a graphical representation of the variation between different learning rates in optimistic and pessimistic cases. It shows the case with initial O&M costs of 36 EUR/kW per year. Different learning rates are taken into the account. The figure is made for the learning rates of 16%, 20%, and 30%, and both optimistic and pessimistic cases. Considering stated, the figure shows the six distinct technological learning curves for O&M costs changes.

As mentioned before, a higher learning rate and optimistic scenario are indicating better results: lower costs. The best performance is shown with the light brown line. That line is made for an optimistic case and a learning rate of 30%. A higher learning rate always gives better results than the lower one, not depending on the case. That line is connected to the highest rise of capacities through the years. All cases mark a drop in costs, which is expected and indicates the correctness of the model. Depending on the learning rate and amount of capacity installed, the curve will have different steep. Starting value is 36 EUR/kW per year. End investment costs values are in the range from 24 to 44 EUR/kW per year, which can be considered as a significant fall regarding this kind of technology. Costs vary in a wide range due to the unpredictability of the development of the repowering process.

Yet again, there are no positive results, costs decrement, between 2040 and 2050. As been clarified before, that period offers new possibilities for further improvements and costs decrements.

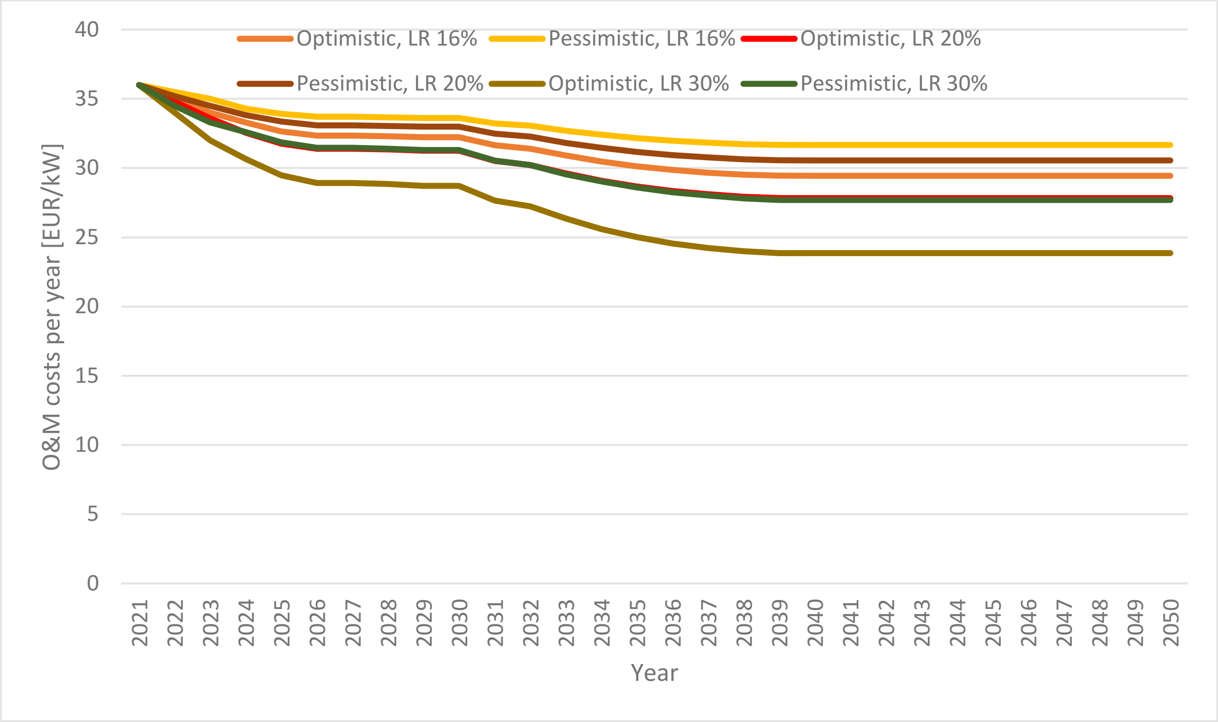

Figure 6.6 Future O&M costs – LR sensitivity analysis

Both investment and O&M costs have similar effects, costs decline in all cases examined. The possible range of the results increases in each case. The further away we are in the future, the greater the uncertainty. In both cost analyses, the highest learning rate gives in the end the best outcomes.

Also, an optimistic case proves to be a more affordable option than the pessimistic one. These costs will certainly vary in the future and may differ from those stated because they depend heavily on capacity development. Not just in Austria but as well in the rest of the world, setting the different learning rates.

6.6.2. Full load hours

In section 5.4 for each turbine in the region, FLH is calculated on two different heights 120 and 150 meters. Only two heights are chosen because of their simplicity. Figure 6.7 presents the one-day energy production of park Zurndorf V, chosen as an example, after repowering, for the optimistic and pessimistic case. For the optimistic case, the turbine used is Vestas, V164, with a rated power of 9,5 MW. For the pessimistic case, the turbine used is Repower, 6M, with a rated power of 6 MW. Also, energy production before repowering is represented. The turbine before repowering was Enercon 101, with a capacity of 6 MW.

FLH for the optimistic case is calculated to be 2786 hours on 120 and 3013 hours on 150 meters hub height, and for the pessimistic case, they are 2597 hours on 120 and 2818 hours on 150 meters. The figure is presented for only 24 out of 8760 possible hours.

The figure shows that the park before repowering is producing more energy than the park in the pessimistic repowering scenario. The installed capacities are the same, the only difference is the manufacturer. For this reason, we can conclude that careful selection of turbines is essential while repowering. On the other hand, the optimal choice (optimistic one) is making significantly greater amounts of energy than before repowering, while the park's capacity is increased just by 3,5 MW.

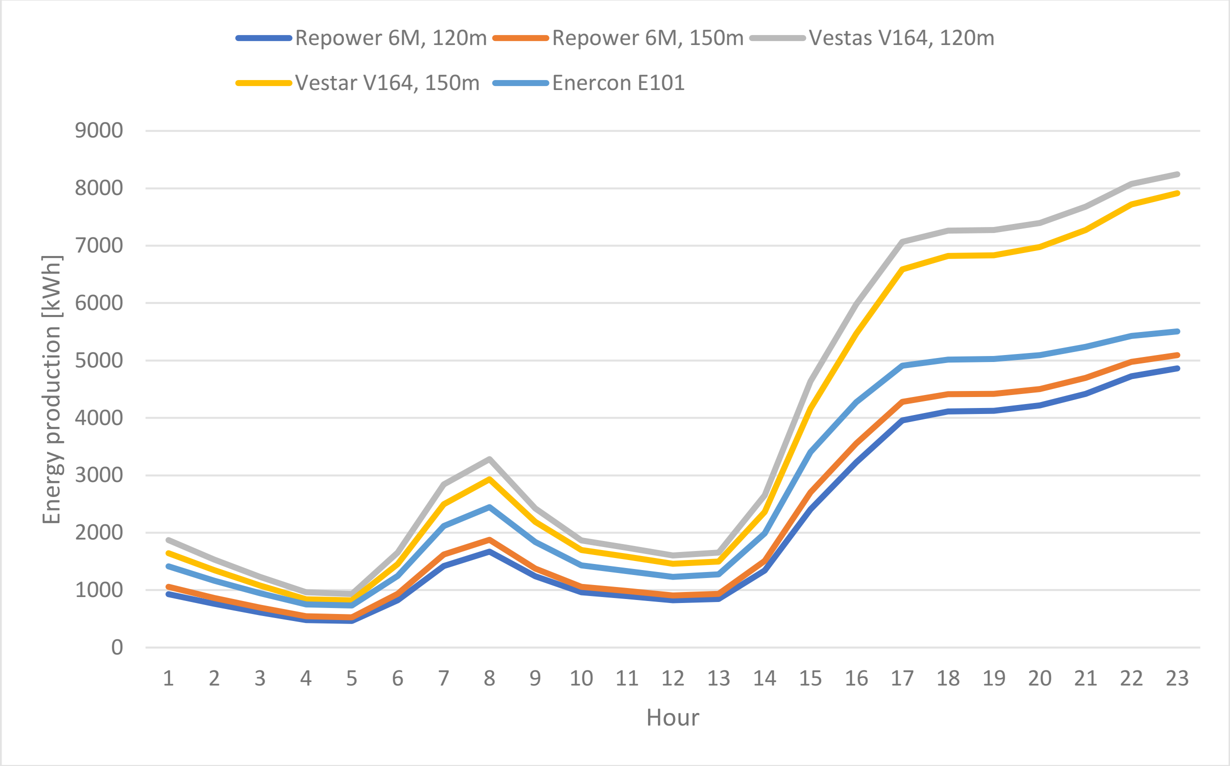

Figure 6.7 Total day energy production before and after repowering for a park Zurndorf V in Burgenland (before repowering – light blue line, after repowering – other four lines)

6.7. Synthesis of the results

Table 6.10 sums up the most essential attained results, comparing them to the initial state in 2020. Results are promising not only for the optimistic, but for the pessimistic scenario as well. Repowering will support the enlargement of capacity and annual energy production in Austria.

After estimating the year of repowering, capacity is determined to be able to reach more than 6000 MW just by repowering the existing plants. If new wind plants were to be installed in Austria in the next years, the repowering potentials would be even greater. Capacities determined for 2050 are double the initial value of around 2800 MW. Which is a great achievement regarding the limiting used surface by not increasing it while repowering. The highest potentials are found in Lower Austria and Burgenland, as seen in table 6.5.

Estimated annual energy production is almost in all cases more than 10 TWh. Total annual energy production is higher than expected in 2050, due to new reporting processes happening after 2030. The increase is greater from 2020 until 2030 than from 2030 to 2050, because in the period from 2020 till 2030 more power plants reach the end of their lifespan and are set to be repowered.

Increment of energy opens the possibility for energy curtailments, which, if used smartly, can be exported and gain revenue. Curtailments are happening in periods where the production from wind is too high, and the whole generation cannot be placed on the market in that hour. They are in the range of 100 to 200 GWh per year in estimated cases. Curtailments are higher in 2050 than in 2030, supplementing the increase in energy. They are rising with the increment of the capacity in the system. They can be reduced, with the possible ability to control renewable sources in the system.

Accumulation of wind capacity affects wind technology costs, due to technological learning. Future costs vary in wide range because of the lack of accurate records on the current costs and not easily predicted learning rates of wind technologies. Comparing the results to the current situation, column 2020, advancement and benefits are evident in all aspects. Investment costs have at least 100 EUR/kW decrement by 2030, and even more by 2050. For large technologies, like wind technologies, a small reduction in costs is essential. Developing a better maintenance system, O&M costs can lower to at least 5 EUR/kW per year by 2050. Higher achievements are possible depending on the construction of new power plants.

Table 6.10 Synthesis of the total potentials due to repowering for 2030 and 2050, compared to the initial situation

Scenario		optimistic		pessimistic	
Year	2020	2030	2050	2030	2050
Capacity [MW]	3120	4353	6238	3681	4668
Energy [TWh]	7	10,3	14,8	8,7	11,1
Curtailment [MWh]	/	143107	285938	98802	126960
Investment costs [EUR/kW]	1200 - 1700	956 - 1390	795 - 1390	1040 - 1587	923 - 1495
O&M costs [EUR/kW]	36-40	28 - 35	23 - 32	31 - 37	27 - 35

As it is shown in the table 4.5 Burgenland and Lower Austria have the highest wind potential in Austria, considering repowering. Already installed wind power plants in convenient locations are just reaching the end of their lives, which makes parks in these regions suitable for repowering process. Other regions have a lower potential for repowering, so the main potentials for wind repowering lay in these two regions.

7. Conclusion

Since now, repowering was considered a great option for the increment of wind capacity. The aim of this thesis was to examine the repowering process in Austria, and if there is a potential for wind capacity growth due to it. From the results of this work, it is seen that repowering provides better use of wind energy and favors the boost of total installed capacity, along with the technology costs reduction. Owing to that, an applied method is providing the anticipated outcomes.

There are evident existing repowering possibilities in upcoming years, while considering the age structure of wind parks in Austria. For this reason, wind capacities and energy production in Austria can reach higher levels. Subsequently, costs of investment and operation and maintenance for wind technologies will decline, by following the technological learning trend. Possible energy curtailments can be traded. Owing to different possible repowering potential, the state of capacity can vary, thus creating an optimistic and pessimistic case. Variation of certain parameters, like learning rate and initial costs, may result in deviation of results.

In conclusion, there are significant potentials for repowering, which could support national energy objectives and increase the share of RES in the energy mix of Austria. Repowering brings many other benefits, as it is seen, in a positive influence on capacity and costs. Whether these potentials are going to be recognized, depends mostly on owners, investors, and incentives.

Further research can be conducted by examining repowering with possible increment in wind park's area, which can give better outcomes. A more detailed analysis of each park, such as considering geographical, grid, social, and economic obstacles, can lead to more precise predictions. A more comprehensive evaluation can be conducted, depending on the additional information about the evolution of wind technologies and future built plants.

References

[1] "What is wind energy?", *GE Renewable Energy* Available: https://www.ge.com/renewableenergy/wind-energy/what-is-wind-energy, accessed: 20.05.2021

[2] A. P. Ferreira and C. B. Vaz, "Performance Comparison of Wind Energy Conversion System Technologies", *Clean technologies* pp. 247–252, 2015

[3] "Advantages and Challenges of Wind Energy - Department of Energy", *Office of Energy Efficiency & Renewable Energy*, available: https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy, accessed: 15.05.2021

[4] M. Junginger, A. Faaij, and W. C. Turkenburg, "Global experience curves for wind farms", *Energy Policy*, vol. 33, pp. 133–150, 2005

[5] I. Komusanac, G. Brindley, D. Fraile, L. Ramirez, "Wind energy in Europe 2020 Statistics and the outlook for 2021-2025", *Wind Europe*, 2021

[6] "Wind in Zahlen", *IG Windkraft*, 2021., Available: https://www.igwindkraft.at/ accessed: 15.05.2021

[7] L. Castro-santos, A. F. Vizoso, E. M. Camacho, and L. Castro-santos, "Costs and feasibility of repowering wind farms", *Energy Sources, Part B Econ. Planning, Policy*, vol. 11, no. 10, pp. 974–981, 2017

[8] R. Karoui, F. Bacha, A. Hasni, and H. Khadraoui, "Analysis of the Repowering Wind Farm of Sidi-Daoud in Tunisia Ridha Karoui Faouzi Bacha Amal Hasn i Hamdi Khadraoui", *IEEE Trans. Ind. Appl.*, vol. PP, no. c, p. 1, 2018

[9] H. Karoui, Ridha; Bacha, Faouzi; Hasni, Amal; Khadraoui, "Repowering of the Wind Farm of Sidi-Daoud", *IEEE*, pp. 316–322, 2017

[10] P. Bezbradica, Marko; Kerkvliet, Hans; Montenegro Borbolla, Ivan; Lehtimäki, "Introducing Multi-Criteria Decision Analysis for Wind Farm Repowering", *IEEE*, March 1998

[11] T. Rubert, D. Mcmillan, and P. Niewczas, “A decision support tool to assist with lifetime extension of wind turbines”, *Renew. Energy*, vol. 120, pp. 423–433, 2018

[12] A. Filgueira, M. A. Seijo, E. Muñoz, L. Castro, and L. Piegari, “Technical and Economic Study of Two Repowered Wind Farms in Bustelo and San Xoán , 24 . 7 MW and 15 . 84 MW respectively”, *IEEE* pp. 545–549, 2009

[13] A. Calvo, G. I. Go, and P. Rı, “Policies and design elements for the repowering of wind farms : A qualitative analysis of different options”, *Energy Policy,* vol. 39, no. 2011, pp. 1897–1908, 2020

[14] R. L. Arántegui and A. Uihlein, “Technology effects in repowering wind turbines”, Wind Energy, vol.23, no. 3, pp. 1–16, 2019

[15] E. Martínez, E. Jiménez, F. Sanz, and J. Blanco, “Life cycle assessment of a wind farm repowering process”, *Renew. Sustain. Energy Rev.*, vol. 93, August 2017, pp. 260–271, 2018

[16] R. Himpler, Sebastian; Madlener, “Repowering of Wind Turbines : Economics and Optimal Timing Sebastian Himpler and Reinhard Madlener”, *Inst. Futur. Energy Consum. Needs Behav. (FCN)*, No. 19, 2012

[17] F. Safaei, N. Tazi, and Y. Bouzidi, “Optimal Topology and Repowering Time for Offshore Wind Turbines”, *2019 6th Int. Conf. Control. Decis. Inf. Technol.*, no. 1, pp. 1344–1349, 2019

[18] T. Zuo, Y. Zhang, K. Meng, S. Member, and Z. Tong, “Collector System Topology Design for Offshore Wind Farm ’ s Repowering and Expansion”, *IEEE* vol. 3029, 2020

[19] P. Hou, P. Enevoldsen, W. Hu, C. Chen, and Z. Chen, “Offshore wind farm repowering optimization”, *Applied Energy,* vol. 208, p. 834-844, August 2017

[20] A. Miketa and L. Schrattenholzer, “Experiments with a methodology to model the role of R & D expenditures in energy technology learning processes ; first results”, *Energy Policy,* vol. 32, pp. 1679–1692, 2004

[21] T. Jamasb, “Technical Change Theory and Learning Curves : Patterns of Progress in Energy”, *The Energy Journal*, vol. 28, no. April 2006, 2015

[22] A. Mcdonald and L. Schrattenholzer, “Learning rates for energy technologies”, *Energy Policy,* vol. 29, pp. 255–261, 2001

[23] P. H. Kobos, J. D. Erickson, and T. E. Drennen, “Technological learning and renewable energy costs : implications for US renewable energy policy”, *Energy Policy,* vol. 34, pp. 1645–1658, 2006

[24] L. Neij, “Experience curves for wind power”, *International Journal of Energy Technology and Policy,* vol. 2, pp. 15–32, 2004

[25] T. Wiesenthal *et al.*, "Technology Learning Curves for Energy Policy Support*", JRC Scientific and Policy Reports,* 2012

[26] A. Krenn *et al.*, “Windatlas und Windpotentialstudie Österreich”, *FG / Klima- and Energiefonds*, November 2011, 2020

[27] M. Stefan and M. Hans, “Neubewertung des Potentials zur Nutzung der Windkraft in Österreich bis zum Jahr 2030”, *IG Windkraft* pp. 1–9, 2020

[28] “Windkraft im Burgenland”, *IG Windkraft*, 2021, Available: https://www.igwindkraft.at/, accessed: 15.03.2021

[29] “Windenergie in Österreich”, *Windfakten*, 2021, Available: https://windfakten.at/, accessed: 15.03.2021

[30] F. Maringer, P. Wonisch, and A. Krenn, “Austria Report 2017”, *IEA Wind*, pp. 1–4, 2018

[31] “Stepping up Europe’s 2030 climate ambition”, *European Comission*, 2020

[32] H. Fechner, C. Mayr, A. Schneider, M. Rennhofer, and P. G., “Technologie-Roadmap für Photovoltaik in Österreich”, *Nachhalt. wirtschaften*, 2016

[33] “Windrad-Landkarte”, *IG Windkraft*, 2021., Available: https://www.igwindkraft.at/ accessed: 15.03.2021

[34] “Einspeisetarife”, *IG Windkraft*, 2019., Available: https://www.igwindkraft.at/ accessed: 15.03.2021

[35] R. Bolz and C. Rupert, “get wet - Gezielte Entwicklung der Windenergietechnologie”, *Blue Globe Foresight*, 2015

[36] B. S. Nivedh, R. P. K. Devi, and E. Sreevalsan, “Repowering of Wind Farms - a Case Study”, *SAGE Journals* pp. 137–150, 2013

[37] “Technology Roadmap - Wind energy”, *Int. Energy Agency*, 2013

[38] “Repowering and Lifetime Extention: making the most of Europe’s wind energy resource”, *Wind Eur.*, 2017

[39] F. Miceli, “How good is the wind farm you are working at? Some indicators”, *Wind farms construction*, 2020, available: https://www.windfarmbop.com/how-good-is-the-wind-farm-you-are-working-at-some-indicators/, 2020, accessed: 15.05.2021

[40] “Förderung Ökostromgesetz”, *Windfakten*, available: https://windfakten.at/, accessed: 20.05.2021

[41] “Open Power System Data – A platform for open data of the European power system”, available: https://open-power-system-data.org/, accessed: 10.05.2021

[42] “Renewables.ninja”, available: https://www.renewables.ninja/, accessed: 20.04.2021

[43] E. Lantz, R. Wiser, and M. Hand, “IEA Wind Task 26 The Past and Future Cost of Wind Energy”, *NREL*, 2012

[44] S. Krohn, P.-E. Morthorst, and S. Awrbuch, “The Economics of Wind Energy”, *EWEA*, 2009

[45] “Wind Power - Renewable energy technologies: Cost Analysis Series”, *IRENA*, vol. 1, no. 5, 2012

[46] N. H. Johnson and B. D. Solomon, “A Net-Present Value Analysis for a Wind Turbine Purchase at a Small US College”, *Energies,* May 2010

[47] I. Staffell and R. Green, “How does wind farm performance decline with age ?”, *Renew. Energy*, vol. 66, pp. 775–786, 2014

[48] M. Stojiljković, “Linear Regression in Python”, *Real Python*, available: https://realpython.com/linear-regression-in-python/, accessed: 20.04.2021

[49] P. Söderholm, “Learning Curve Analysis for Energy Technologies : Theoretical and Econometric Issues”, *EPRG,* January 2003, 2014

Abbreviations and acronyms

CO_2	*Carbon Dioxide*
EU	*European Union*
EUR	*Euro*
FIT	*Feed-In Tariff*
FLH	*Full Load Hours*
GEA	*Green Electricity Act*
GW	*Gigawatts*
h	*hour*
IRR	*Internal Rate of Return*
ISDN	*Integrated Services*
kW	*Kilowatts*
kWh	*Kilowatt hour*
LCOE	*Levelized Cost of Energy*
lt	*lifetime*
LR	*Learning Rate*
m	*meter*
MW	*Megawatts*
MWh	*Megawatt hour*
η	*Efficiency*
NPV	*Net Present Value*
NREAP	*National Renewable Energy Action Plan*
OeMAG	*Ökostromabwicklungsstelle*
O&M	*Operation and Maintenance*
PI	*Profitability Index*
PV	*Photovoltaic*
RES	*Renewable Energy Sources*
TWh	*Terawatt hour*

Appendix

CODE 1 – finding repowering year for each park in Austria

```
def repower(a): # function to check that park a is successfully repowered
    park[a]["repow"] = 1 #set repowering indication variable to TRUE


for a in range(number_of_parks): #loop for a number of all wind parks in model (in Austria)
    while (park[a]["repow"] == 0): #loop until the park is repowered
        CF_om = park[a]["C_om"]
        if (park[a]["lifetime"] > 25): #if park is older than 25 years, go straight to repowering
            repower(a)

        if (park[a]["lifetime"] > 10): #check if park is older than 10 years, if yes: consider repowering
            if(park[a]["NPV"] < 0): #if NPV is negative calculate it to obtain positive value
                CF_dis = 0
                for i in range(1, 14):  #calculating cash flow for first 13 years, based on FIT
                    CF = 0
                    for n in range(8760):
                        CF = CF + park[a]["en"][n] * wind_price_fit[i + (park[a]["year"] - 1994)] #using FIT
                    CF_dis = CF_dis + CF / (1 + r) ** i #discout rate r=2,7%
                    CF_om = CF_om * (1 + 0.1) #O&M costs rising 1% per year

                for i in range(13, park[a]["lifetime"]): #calculating cash flow, based on day-ahead prices
                    CF = 0
                    for n in range(8760):
                        CF = CF + park[a]["en"][n] * wind_price_market[n]
                    CF_dis = CF_dis + CF / (1 + r) ** i
                    CF_om = CF_om * (1 + 0.1)

                park[a]["NPV"]  = CF_dis - park[a]["C_inv"] - CF_om #NPV determined


            if (park[a]["NPV"] >= 0):
                print('NPV is greater than or equal to 0, repowering is possible!')

                if(park[a]["lifetime"] >= 20): #if park is older than 20 years, go straight to repowering
                    repower(a)
                else: #if not, check the expenses due to the O&M costs increment and efficiency decrement
                    CF_loss = 0
                    CF = 0
                    for k in range(5):
                        CF_om_loss = CF_om * (1 + 0.1)
                        if (park[a]["lifetime"] <= 13): #FIT price if younger than 13 years
                            for t in range(8760):
                                CF_loss = CF_loss + park[a]["en"][t] * (1 - (1 - 0.016 *(park[a]["lifetime"]
                                             + k)))  * \ wind_price_fit[park[a]["lifetime"] + k]
                                CF = CF + park[a]["en"][t] * (1 - 0.016 * (park[a]["lifetime"] + k))
                                    wind_price_fit[park[a]["lifetime"] + k]
                        else: #after 13 years, use of market price
                            for t in range(8760):
                                CF_loss = CF_loss + park[a]["en"][t] * (1 - (1 - 0.016 *(park[a]["lifetime"]
                                           + k))) * \ wind_price_market[t]
                                CF = CF + park[a]["en"][t] * (1 - 0.016 * (park[a]["lifetime"] + k)) *
                                           wind_price_market[t]


                    losses = CF_loss + CF_om_loss #total cash losses


                    if (losses >= CF):  #if cash losses are greater than or equal to incomes, do repower
                        repower(a)
                    else:
                        park[a]["lifetime"] = park[a]["lifetime"] + 1 #if no repowering, check next year
            else:
                park[a]["lifetime"] = park[a]["lifetime"] + 1 #if no repowering, check next year
        else:
            park[a]["lifetime"] = park[a]["lifetime"] + 1 #if no repowering, check next year
```

CODE 2 – optimization for determining repowered park capacity and the number of turbines

```
#Model for every turbine j in the region, having 3 different new turbines options
for i in range(number_of_turbines): #number of turbines in region
    k = 0
    for j in range(0, 3): #different turbine capacities
        m = Model("XYZ_Region") #XYZ - name of region


        # defining variables: new capacity and number of new turbines
        Cap_new = m.addVar()
        n_new = m.addVar(vtype=GRB.INTEGER) #number of turbines is going to be an integer value

        m.addConstr(Cap_new >= xyz_region_turbines[j]["cap"]) #new installed capacity should be the same or
greater than the old one
        m.addConstr(n_new <= park[i]["nr"]) #number of new turbines should be the same or lower than in old
park
        m.addConstr(Cap_new >= park[i]["cap_tot"]) #capacity of one turbine is the lowest possible capacity
of the park
        m.addConstr(Cap_new == n_new * xyz_region_turbines[j]["cap"]) #new capacity is equal to the number
of new turbines multiplied
        if (park[i]["nr"] == 1):
            m.addConstr(n_new == 1) #if there was only one turbine in park, the number stays the same
        else:
            m.addConstr(n_new * d[j] <= park[i]["nr"] * park[i]["D"]) #application of 4 diameters rule, new
park takes up same or smaller area


        def goal():
            capacity_final = Cap_new
            return capacity_final

        #optimization goal is to install maximal possible capacity on a certain area
        m.setObjective(goal(), GRB.MAXIMIZE)
        m.optimize()
```

CODE 3 – linear regression calculation for the prediction of the total capacities in Austria

```
from sklearn.linear_model import LinearRegression


x = [2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021] #initial data - years
Y = [1015, 1103, 1380, 1695, 2102, 2426, 2654, 2849, 3039, 3159, 3120, 3396] #initial data - capacity


X = np.array(x).reshape((-1, 1)) #data formatting
y = np.array(Y)

model = LinearRegression()
model.fit(X, y)

xx = np.arange(2021, 2051, 1) #years that are going to be predicted
X_predict = np.arange(2021, 2051, 1).reshape((-1, 1))  #prediction in given years
y_pr = model.predict(X)
y_predict = model.predict(X_predict) #making a prediction
print(y_predict)
```

CODE 4 – unit commitment for curtailment approximation

```
#fuel prices EUR/MWh average 2015
price_oil = 38.25
price_gas = 20.05
price_bio = 37.04

#initialization of variables to determine
for t in range(1, 8760):
    Eslack[t] = m.addVar(name='Curtailment', lb=-1000000, ub=0) #variable for curtailment
    Emissing[t] = m.addVar(name='Energy missing', lb=0, ub=1000000) #variable for energy missing
    Eoil[t] = m.addVar(name = 'PP oil', lb=0, ub = 288) #oil plants, capacity of 288MW
    Ebio_1[t] = m.addVar(name = 'PP bio 1', lb =0.2*393, ub = 393) #bio plants, capacity 393 MW, minimal
load 20%
    Ebio_2[t] = m.addVar(name = 'PP bio 2', lb =0.35*290, ub = 290) #bio plants, capacity 290 MW, minimal
load 35%
    Egas[t] = m.addVar(name = 'PP gas all', lb=0, ub=7048) #gas plats, capacity 7048 MW


for n in range(len(capacity_gas)):
    for t in range(1, 8760):
        Egas_one[n, t] = m.addVar(name= 'PP gas', lb=0.4*capacity_gas[n], ub=capacity_gas[n])

#pumped hydro variables
for t in range(0, 8761):
    StateOfCharge[t] = m.addVar(name='\nStateOfCharge - hydro[%d]' %t, lb=0, ub=5936)
    Pdis[t] = m.addVar(name='\nPdis[%d]' %t, lb=0, ub=2971) #pumped hydro discharging
    Pch[t] = m.addVar(name='\nPch[%d]' %t, lb=0, ub=2971) #pumped hydro charging

m.addConstr(StateOfCharge[0] == 0) #pumped hydro storage in initial state


for t in range(1, 8760):
    m.addConstr(StateOfCharge[t] == StateOfCharge[t - 1] + Pch[t] * 0.8 - Pdis[t] / 0.8) #pumped hydro
storage equation
    m.addConstr(Egas_one[0, t] + Egas_one[1, t] + Egas_one[2, t] + Egas_one[3, t] + Egas_one[4, t]
                + Egas_one[5, t] + Egas_one[6, t] + Egas_one[7, t] + Egas_one[8, t] + Egas_one[9, t] +
Egas_one[10, t]
                + Egas_one[11, t] + Egas_one[12, t] + Egas_one[13, t] + Egas_one[14, t] == Egas[t])
    m.addConstr(E_PV[t] + E_wind[t] + 0.41*Eoil[t] + 0.45*Ebio_1[t] + 0.46*Ebio_2[t] + 0.525*Egas[t] +
Emissing[t]
                + Eslack[t] - Pch[t] + Pdis[t] == Demand[t]) #generation equation equal to demand in all
hours


def objective(): #objective to minimize all prices
    price=0
    for t in range(1, 8760):
        price += Eoil[t]*price_oil + Egas[t]*price_gas + (Ebio_1[t] + Ebio_2[t])*price_bio + Emissing[t]*100
+ (-Eslack[t])*150
    return price #having the highest price, curtailment (Eslack) is a last option for system

m.setObjective(objective(), GRB.MINIMIZE)
m.optimize()
```