MSc Program
Renewable Energy Systems

Repowering of Wind Power Plants

A Master's Thesis submitted for the degree of
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Affidavit

I, **MATHIAS MAGYAR, BED**, hereby declare

1. that I am the sole author of the present Master's Thesis, "REPOWERING OF WIND POWER PLANTS", 64 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 05.10.2023

Signature

Acknowledgements

Für eine alte Freundin.

Abstract

The aim of this thesis is to provide an insight into the financial attractiveness of repowering a wind farm, which is nearing its approximate end of turbine lifetime. An industry standard financial viability calculation using the Net Present Value methodology is performed which is then expanded on by applying Real Option Analysis to the problem, with the intention of adequately capturing the true value of a to be repowered wind farm. By focusing on an existing wind farm in Austria, it is shown that due to the historic policy design, repowering will become an increasingly relevant issue in the country's wind energy market. Thus, actors in the industry are confronted with upcoming managerial decisions, which the Real Option Approach adequately includes in its methodology. The calculation exhibits a clear indication that, under the preset input parameters, a repowering decision before the end of turbine lifetime is the most financially rewarding decision.

Keywords: Renewable Energy, Real Option Analysis, Repowering, Wind power.

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1 Introduction

Imagine you are ten years away from retirement. You can already see your well-deserved parting from getting up every early morning and leaving for your place of occupation on the horizon. Nonetheless, you aim to maximize your earnings in your last decade of employment. You do so by applying every single year for a job. However, once you decide on taking a new job you cannot change positions until you retire. Now, by statistical destiny, the jobs you are offered every year pay either € 50 or € 100 per hour, whilst always having the option to decline. The probability of receiving an offer for the high or low paying position is exactly a 50/50 chance. Not a bad situation one might think! However, as mentioned before, once you accept either of the positions, you are stuck in this employment relationship until you retire, meaning that once you accept one of the yearly job offers, you must stay in that position until you enter retirement. Thus, you ask yourself: what is the best strategy to receive the maximum total salary? Should you take an early offer that pays € 50, or should I rather wait for the first € 100 job? This peculiar pickle of a problem was first discussed by Neumann & Morgenstern in 1944, keying the process of backwards induction to solve this dilemma of optimally stopping your decision options at the perfect time (von Neumann and Morgenstern 1947).

1.1 Motivation

Now you might think; what does this have to do with the title of this thesis? Well, similarly to the lucky position the subject of the previous paragraph, the owners and operators of existing wind farms, might find themselves in as well. They have a functioning and operating wind farm connected to the grid, generating green electricity and impressive revenues for themselves. However, the wind farm is getting old. After 15 years of operation, they start to think about replacing the old plants with newer, more efficient ones, that would generate a certain amount of electricity more. Thus, like the subject of the previous example above, they have a similar decision to make. Continue with the comparably low-production, existing farm (the € 50 offer), or wait and see how the € 100 (repowering) offer develops. Now, how do they identify the value of this option to repower. What actual numeric benefit do they currently have of holding this option? And when does the value of actually repowering the plant supersede the value of not doing so? This is where the similarities of von Neumann's and Morgenstern's reflections start to overlap with the topic of renewable electricity production by making use of the potential energy of wind.

1.2 Objective, Key Research Questions and Hypothesis

The key objective of this work is to implement a Real Options Approach to a repowering scenario for a wind farm located in Austria using an EXCEL tool, with the hypothesis being that by conducting such a Real Options Analysis the calculated value of the plant increases. This calculated, added value might prove itself of interest for wind farm operators and/or owners in order to better evaluate the asset at hand. Moreover, if a repowering or sale of the wind farm is to be executed, decision makers are empowered to view their asset from an additional, financial perspective. In order to elaborate on this, let us continue the train of thought our wind farm owners and operators very well find themselves having now. Up until recently, they valued their wind farm using a very common approach by adding up the revenues they expect over the coming years and discounting them by a certain factor. This sum-value was the monetary benefit they thought of having in their future pockets. However, now they come to realize, that there is a sort of hidden value in their wind farm, which a simple cost-benefit analysis does not capture; the so-called real option value of the plant. The way they used to calculate their revenues, rid them of their managerial flexibility. Having realized this, they enter the fictious rabbit hole of Real Option Theory. What are options? How do we identify them? How do we calculate the value of these options? To those questions – in the context of wind energy in Austria - this thesis also aims to provide an answer to.

However, before we dive into the world of wind energy and real option methodology, it is important to ask ourselves: why? Why is it necessary to conduct such an analysis. Although, it is not a matter of life and death, the motivation behind this thesis is one of curiosity. Real Option Theory has been roaming around the academic and financial sphere for several decades. However, its use in everyday business, is limited. By applying a sound, real option approach, it is sought to investigate if by doing so we get to better understand why this methodology is not applied and if it might be advisable to rid oneself of the status-quo NPV habitus and to start exploring the shores of Real Option Methodology. Again, the hypothesis being that by conducting a real option analysis, the value of a non-repowered existing wind farm increases, thus creating incentives for wind farm owners and operators to start to include this approach into their decision-making processes.

1.3 Policy Context

Global warming is the ultimate source of the research problem this thesis focuses on. The following paragraphs will elaborate on how the issue of global warming directly correlates with the incoming repowering wave in Austria. In the period between 2011-2020 global surface temperatures were 1.1 degree Celsius above the respective 1850-1900 time-span. Accepting that this increase in temperature is caused by human activities, forms the basis of climate change mitigation by adapting greenhouse gas emissions caused by humanity. The role of mankind is inarguable, with the first sentence in the 2023 report of the International Panel on Climate Change (IPCC) being:

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming (…) (IPCC 2023, 4).

According to the IPCCs 2014 report on Mitigation of Climate Change, 25% of global greenhouse gas emission can be allocated to the economic sector of electricity and heat, under which, naturally, electricity production falls as well. Thus, reducing the impact which means of energy production that are based on fossil technologies have, is a vital part of reducing green-house gas emissions (IPCC 2014, 9).

The sound scientifical basis of human made climate change resulted in international agreements, most notably the Paris Agreement, which was signed by 196 parties, including Austria, at the 21st United Nations Climate Change Conference in Paris, France and which ultimately entered into force at the end of 2016. In this landmark paper the signatories mark the goal of keeping “the increase in the global average temperature to well below two degree Celsius above pre-industrial levels" as well as "[limiting] the temperature increase to 1.5 degrees Celsius above pre-industrial level" (United Nations 2015, 3).

Signatories are legally bound to act upon their promises made in the Paris Agreement. In 2018, the Austrian government published its climate and energy strategy - referred to as #mission2030. In said paper, Austria strengthens its promise to follow up on the goals stated in the Paris Agreement. This is exactly where the repowering of the Austrian wind energy portfolio comes into play. The mission paper states that Austria aims to increase the percentage of renewable energies in the gross final energy demand to 45-50% by 2030. Furthermore, the total energy demand (including renewable energy exports) shall be 100% covered by national renewable energy production (Bundesministerium für Nachhaltigkeit und Tourismus and Bundesministerium für Verkehr, Innovation und Technologie 2018, 14).

1.4 Structure of the Thesis

However, before B and C comes A, thus, the thesis needs to set the scene. This is achieved by giving the reader a concise introduction into the peculiarities of generating electricity from wind. Aforementioned, overview can be found in Chapter 2. Background Information, which is split into two subsections; on the historical- as well as technical-aspects of using the power of wind. Starting off with the historic evolution of wind energy, showing that in the coming years, repowering will continue to establish itself as a key issue in the wind energy industry. Next, the main physical principles are explored. These are important to understand, as a repowered plant will produce more electricity not just because the generator itself has a higher name plate capacity, but also because the wind differs in various heights and wind speed influences production as much as no other physical factor does.

Continuing with the macro-economic side of things, Chapter 2. will continue to take a look at what role subsidy schemes play in the sector and especially how the timing of the legislative framing is directly connected to an influx in repowering situations, introducing the term of Repowering Waves. The situation is deeply explored using the example of Austria.

Next, in Chapter 3. the major micro-economic part comes into play. An overview over the classic Net Present Value economic evaluation tool is provided. This is then expanded on by the concept of Real Option Theory, which is the main topic of this thesis. A hands-on calculation methodology is presented, which shall enable decision makers to benefit from their managerial flexibility. The binomial Real Option Model is fed by real world data from a wind farm in Austria. The data is assessed and adapted for the repowering scenario, by making use of the wind shear phenomenon. As the key financial variable, the electricity price situation in the European electricity market is described and its volatility is assessed using a Monte Carlo Simulation. In addition, Chapter 4 introduces the main input parameters. These input parameters are either calculated or retrieved from literature and span topics such as Investment and running costs as well as an in-depth analysis of the revenue-stream, which can be expected from the plant. The results from the Real Option Analysis, which is performed using the outlined methodology and input-parameters, are presented in Chapter 5. A concise conclusion in Chapter 6 lets the reader revisit the entirety of the thesis. Furthermore, an input into possible future research is provided.

2 Background Information

Renewable energies have established themselves as one of the key sources for electrical energy in today's world. Furthermore, electricity generation capacity-increases, predominantly utilize renewable sources, especially wind and photovoltaics (International Energy Agency 2022, 292). However, making use of the massive renewable potential has been seen as a novelty in the energy business for the most part of the 20th century. Besides hydropower, utilizing and capitalizing on natural phenomena like solar-irradiation and wind, has only for the past twenty years really taken off. This is interesting to note when considering the fact that for centuries wind has indeed been used as a source of energy. Although be it in its direct, mechanical form, in, for example, windmills for grinding agricultural products, or as a transportation device used in various nautical activities. For a comprehensive history of wind energy use, see Erich Haus epic Windenergy "Windkraftanlagen" (in German), especially Chapters one and two. What is most important to note is the lexical differentiation between windmill and wind power plant. The distinction essentially being, that, on the one hand, windmills make use of the rotational, mechanical energy as the final energy being used by the consumer. And, on the other hand, wind power plants, which convert the rotational, mechanical energy into electricity using a generator, which would then in this case be the final energy produced, if it is consumed by an end-user (Sathyajith 2006, 3–6).

2.1 Using the Power of Wind

2.1.1 Historical Aspects

The first wind power plant which converted mechanical energy directly into electricity was conceived at the end of the 19th century in Austria. Recently, new research has shown that contrary to the existing status quo neither the Scottish wind pioneer Byth nor the French inventor de Goyon were the first to directly generate electricity form a wind mill. As previously stated, this achievement should rather be attributed to the Austrian Josef Friedländer, who in 1883 during the Vienna

International Electrical Exhibition installed a 6.6 meter diameter Halladay turbine, see Figure 1 ("Austrian Was First with Wind-Electric Turbine Not Byth or de Goyon" 2023).

Figure 1: The First Wind Turbine used for Electricity Production

Translation of the conference brochure depicted in Figure 1:

International Electrical Exhibition Vienna 1883 (in bold)

Cable car with electrical drive for the transportation of coal to the exhibition's boiler house above the roof of the north gallery. Constructed by the Leobersdorfer Maschinenfabrik und Eisengiesserei

Research on using the power of wind in order to produce electricity continued and was mainly being driven by two factors. Firstly, providing electricity to secluded areas without grid access and, secondly, reducing the dependency on fossil fuels, especially oil. The first large-scale installations which adhere to our modern understanding of wind farms were erected in the 1980's in California. Antecedently, following legislative changes in European countries, starting with Germany, the financial viability of large-scale wind energy projects was created and thus the 1990s saw the erection of the first wind farms on the European continent (Hau 2016, 59–63).

2.1.2 Technical Aspects

Wind is the movement of the atmospheric gas. In our planet earths case, the atmospheric gas or 'Air' is a mixture of approximately 78 percent Nitrogen, 21 percent

Oxygen and one percent other gases. The elemental composition of a gas defines its mass. The following statements are imperative to assess the power of wind. The kinetic energy of an airmass (*m*), which is moving at a velocity of *v* is represented by:

$$E = \frac{1}{2} m v^2$$

Considering now that a wind turbine sweeps over a defined amount of space, being the cross-sectional area A, the kinetic energy which can possibly be harvested by the turbine, at an air density of ρ_a is expressed as

$$E = \frac{1}{2}\, \rho_a\, v\, V^2$$

assuming that v is the volume of air which is being swept by the rotor. Now, including the factor of time; this volume of air being affected by the rotor per unit of time is equal to the cross-sectional area of the rotor (A_T), resulting in

$$P = \frac{1}{2}\, \rho_a\, A_T\, V^3$$

This shows that the available power is mostly driven by the velocity of the wind followed by the density of the air and the swept area of the rotor. Knowing this, it can be deduced that a larger rotor diameter is to be targeted to achieve higher power outputs (Sathyajith 2006, 11).

Now knowing that the velocity of the wind is a key parameter for available power, the wind shear phenomenon, which refers to the fact that the wind speed increases with distance to the ground, lets us deduce that greater nacelle heights are to be sought after. The wind shear, follows a logarithmic wind profile which will be described more closely at a later point, in Section 4.3 of this thesis (Hellmann 1914).

Accepting that extracting 100 percent of the kinetic energy from the wind by a wind turbine, which would result in a windspeed of 0 behind the rotor, is impossible, the Betz Coefficient has to be regarded. Betz realized that the reduction of the windspeed and the resulting tailback, results in the phenomenon that some of the approaching air is kept from passing thorough the rotor. By applying Newtonian fluid dynamics Betz derived that a maximum of 59.3 % of kinetic energy can be extracted (Betz 1920).

Knowing that especially the wind velocity and the area swept by the rotor impacts the power which is extracted, an increase in nacelle-height (which will give access to higher windspeeds in greater heights) as well as longer rotor blades must result in higher possible yields. This is the physical basis of why bigger turbines, both in terms of nacelle height and rotor blade length, results in higher yield, creating the foundation for the financial viability of repowering wind farms.

Besides the just described increase in yield, it is essential to realize that wind turbines have a relatively short lifetime in comparison to fossil or nuclear power-plants, the question arises what potential actions can be taken when end of lifetime has been reached. The lifetime of wind turbines is dependent on various factors such as location, wind conditions (especially gustiness), occurrence of extreme weather events (mainly lightning strikes), maintenance and more. Considering the just mentioned factors a wind turbine, which is located close to the sea and consequently additionally affected by corrosion due to salination, is exposed to gusty wind conditions and thunderstorms, which increases the risk of lightning strikes, whilst being badly maintained will generally have a lower lifetime than most other reference wind turbines. It is typically assumed that the average technical lifetime of a turbine revolves around 20 years. Thus, the operator and/or owner of the wind turbine has to make a decision at some point in the future on what to do with the installed plant. The most likely options are to dismantle the old turbine and replace it with a new one, refurbish the old turbines to extend their lifetime or to dismantle the turbines and abandon the project as a whole (Abadie and Goicoechea 2021, 7). In the next section it is shown why and how, prevailing and future subsidy schemes influence the decision on undertaking such an investment.

2.2 Wind Power in Austria: History, Policy and Portfolio

In order to pinpoint the reason for the first erection of wind farms, it can be noted that an increase in renewable energy production, was, like any other form of utility scale electricity production, heavily dependent on subsidies. Thus, if legislative changes provide incentives to invest in, for example, wind energy production technologies, a subsequent uprise in new installations of such technologies is evident.

However, financially attractive subsidies for renewables alone do not automatically foster an investment uprise in such technologies. It has been shown that financial support for other technologies has to be on a level which do not make these non-renewable technologies financially more attractive than their renewable counterparts. (Krozer 2022, 134–37). In order to illustrate the importance of subsidies for the expansion of a country's renewable portfolio, this thesis shall look at the example of Austria.

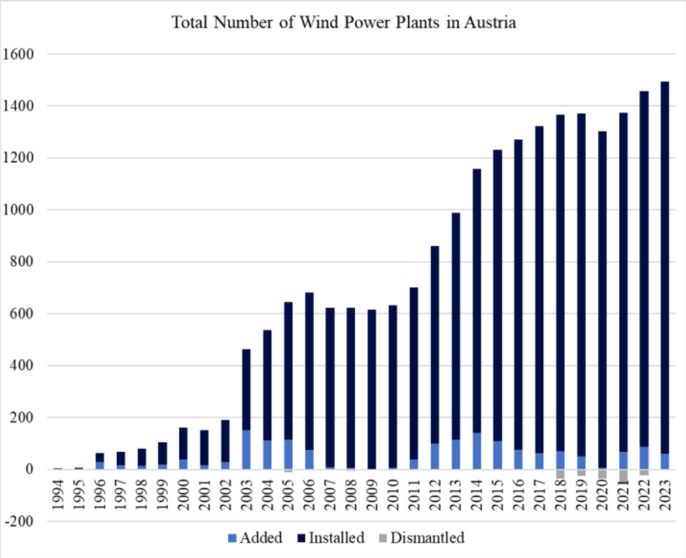


Figure 2: Total Number of Wind Power Plants in Austria (IG Windkraft 2023, 15)

Austria experienced its first episode of massive wind energy installations after an extensive federal subsidy program was ratified in 2002 (*Gesamte Rechtsvorschrift Für Ökostromgesetz, Fassung Vom 31.12.2002* 2002), which resulted in the creation of 455 new wind turbines over the course of the following four years from 2002 until 2006. After the exploitation of the subsidy funds, new installations dropped massively post 2006 (see Figure 2). In 2012 the Austrian state created another legislative package which again caused an impressive spike in new wind turbine installations (*Ökostromgesetz 2012 - Bundesrecht Konsolidiert, Fassung Vom 01.06.2023* 2012). As can be seen in Figure 2, over the next five years, from 2012 up until 2017, 545 new turbines were erected.

Thus, it can be concluded that subsidy schemes naturally play an important role in deciding on going forth with an investment. Again, making it reasonable to analyze the prevailing and upcoming subsidy schemes in Austria, as the financial attractiveness of these subsidy schemes will predetermine the future installation of wind power plants, be it new ones or the repowering of existing farms. In 2022, a new subsidy scheme, which now focuses on market premiums instead of fixed feed in tariffs was ratified (*Erneuerbaren-Ausbau-Gesetz - Bundesrecht Konsolidiert, Fassung Vom 04.06.2023* 2023). The wind energy industry, although having some worries concerning the market premium system as well as the timeline of ratification, responded positively, indicating that this legislation will indeed have a positive impact on new wind power plant installations in Austria. Additionally, the support period for a subsidized project was extended from 13 to 20 years, providing investors with more long-term financial security, decreasing investment risks even more (IG Windkraft 2021). Thus, for future installations, repowering will be the preferred option after approximately two decades of operation. It becomes evident that the owners and operators of the wind power plants which were erected during the first expansion period of the Austrian wind energy portfolio, are now being confronted with the question whether to repower or not. To illustrate the approximate magnitude of the coming repowering wave, it was calculated that in the years 2002-2007, 455 new turbines were erected. As Figure 1 shows, there has been a notable surge in decommissioning of plants between 2018 and 2022, resulting in 103 wind power plants being dismantled. It would be incorrect to assume that these 103 wind turbines were all at their approximate 20 years of lifetime, as many wind farms younger than 20 years were repowered due to the financial attractiveness of the resulting capacity increase. This capacity increase is attributed to the fact that newer turbines, with greater nacelle heights as well as longer blades, power larger generators with higher per turbine capacity. A prime example for such a under maximum lifetime repowering would be a wind farm in Lower Austria which was repowered after 15 years of operation (Rittler 2022). Thus, some of the 103 decommissioned turbines of the period between 2018 and 2022 must be deducted from the 455 turbines which were erected in the first extension period. Let us assume that 55 turbines of the first extension period have already been repowered, leaving us with 400 turbines closing in on their 20 years lifetime.

Additionally, to accommodate for the goals stated in the above mentioned #mission2030 paper, it is the intention of the Austrian government to install the capability of producing an additional 10 TWh of wind energy by the time of 2030 (*Erneuerbaren-Ausbau-Gesetz - Bundesrecht Konsolidiert, Fassung Vom 04.06.2023* 2023, art. 4(4)). In order to contextualize the rather abstract value of 10 TWh, let us assume a reference plant in Austria which is exposed to 2.500 full load hours per year. (*Erneuerbaren-Ausbau-Gesetz - Bundesrecht Konsolidiert, Fassung Vom 04.06.2023* 2023, art. 7(4)) with a state of the art 5 MW of capacity. This results in 12.500.000 kWh, or 0,0125TWh of produced electricity per year and turbine. Dividing this value with the 10 TWh goal, results in a need of an additional 800 turbines. In terms of needed raw installed capacity, assuming a reference 2.500 full load hours, an additional 4.000 MW of installed capacity are needed. The before mentioned figure of 800, 5 MW wind power plants, is based on a sound calculative basis, and indeed shows that the need for a deeper look into the intricacies of the 10 TWh goal is justified.

To gain an insight into the electricity system wide effects which the repowering wave will have, it is necessary to estimate how many turbines will be re-erected in a repowering scenario. As calculated above, approximately 400 turbines will be repowered in the coming years. However, as has been previously stated, due to a necessary increase in distance between the turbines and from settlements the number of re-erected turbines will definitely decrease. Let us first take a look at the increase in distance between the turbines. The distance is dependent on the main wind direction and the size of the rotor blades (Torabi 2022).

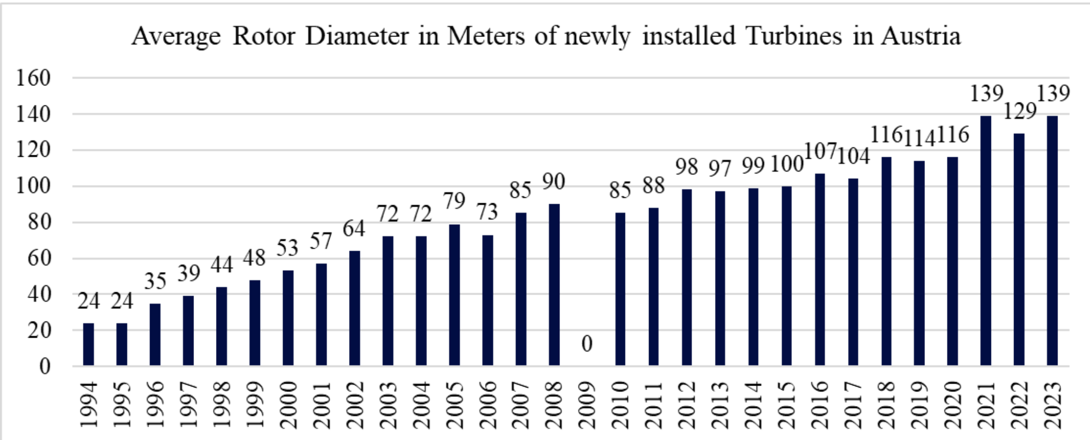


Figure 3: Average Rotor Diameter in Meters of newly installed Turbines in Austria

Figure 3 illustrates that in the years between 2003 and 2007 of the first wind energy expansion phase in Austria the rotor diameters of newly installed turbines ranged from 72 to 79 meters. Since then, rotor diameters have approximately doubled in length, thus increasing the needed space between the turbines by a factor of two resulting in half of the initial turbines being able to be re-erected (Hau 2016, 106–9; IG Windkraft 2023, 14). Legislation concerning distance between wind power plants and settlements zoned as housing is directed by each state in Austria. The largest wind energy potential is in the east of Austria, mostly in the federal states of Lower Austria and Burgenland ("Windatlas Österreich" 2010). In Lower Austria and Burgenland the minimum distance to settlements zoned as housing is 1.200 meters (*Burgenländisches Raumplanungsgesetz* 2019; *NÖ Raumordnungsgesetz* 2014). However, additional distance requirements have to be regarded especially concerning noise emissions. Larger turbines tend to subject their environment to increased noise emissions, thus resulting in tougher distance restrictions. However, this is assessed case by case and subjected to various parameters, on average an increase in distance and thus a decrease in possible turbines being reinstalled is nevertheless unavoidable (Hau 2016, 670–78). Let us assume a conservative 10% of turbines, which will not be able to be repowered due to noise emissions, resulting in a total of 180 turbines which will effectively be repowered.

From an investors point of view, the challenges which arise with turbines nearing their approximate end of life are plentiful. Interestingly, the zoning restrictions mentioned in the previous section could ultimately result in wind farm owners and operators not deciding on repowering as the potential gain from newer, larger turbines could be mitigated massively, as said restriction could decrease the number of new turbines, or the maximum size and thus capacity, in such a way that it would not be financially advisable to repower. Nonetheless, assuming that the wind farm is located in an area where such issues do not arise (i.e. large distance from settlements, with distance requirements this far prescribed by legislation not focusing on housing), the overarching modus operandi will be financial appeal. Thus, the main interest will be the possible additional profit, which is mainly influenced by CAPEX, OPEX and electricity sales. Contrasting the cashflows of the repowered farm with that of the existing will provide an indication as to whether or not it is indeed financially advisable to repower. In addition to the micro-economical perspective, the repowering wave in the coming years will naturally also have an effect on the electricity system itself. 400 Turbines with an average installed capacity of 1,875 MW will be subsequently replaced by turbines of the five- or six-megawatt class (see Figure 4).

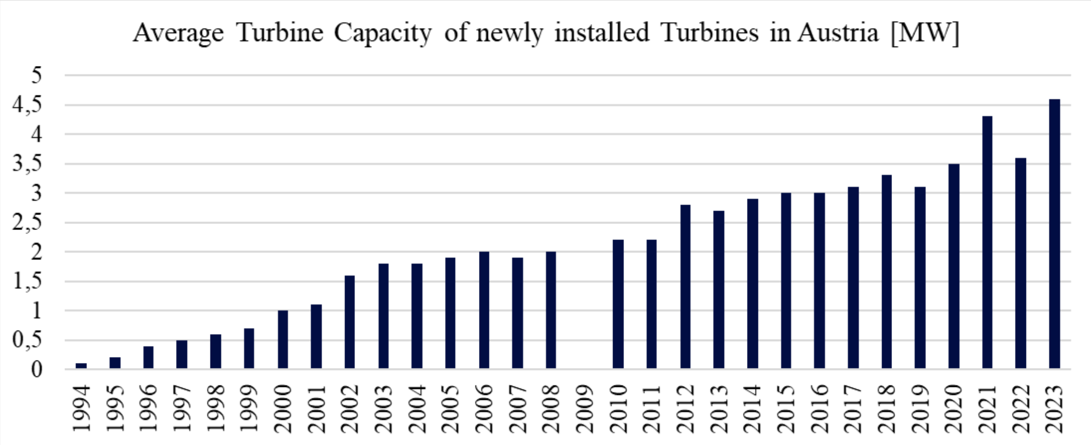


Figure 4: Average Turbine Capacity of newly installed Turbines in Austria (IG Windkraft 2023, 13)

It would be misleading to assume that the repowering process will conclude in the approximate same number of turbines. This is due to the fact that a repowered wind farm will usually have less turbines than were previously installed. The much larger rotor diameters make it necessary to increase the distance between the turbines, as well as increasing the distance to settlements (Hau 2016, 106–9, 670–78). Nevertheless, the repowering of the first expansion phase will indeed result in an impressive wind energy capacity increase potential for Austria. However, from an electricity system perspective more is not always better. The volatility innate to certain renewable energies, including wind energy, represents a challenge to the electricity system, as the fluctuation in production is generally detached from demand. The issue of system conducive wind power plant design is thus becoming more relevant. Main objective of system conducive power plants is providing a more stable and predictable output. For the case of wind power, research has shown that wind turbines that combine maximum possible nacelle height and swept area, whilst running a down-sized generator, tend to achieve the before-mentioned objectives (DIW Berlin 2015).

3 Methodology

From a methodological perspective, this thesis commenced with a classical hypothesis which ought to be able to be tested. The hypothetical background is supported by a literature analysis, spanning the current state of research. Then, the hypothesis is tested via a modelling process based on an EXCEL simulation. The literature used is either peer reviewed and/or authored by experts in the field and institutions that have proven themselves to be reliable sources. Specifying on the concrete method, the thesis focuses heavily on real option analysis research. As there are varying methodological notions in real option analysis it is necessary to define what exact theoretical real option model this thesis follows. However, as has been stated before, the nomenclature in the field has not yet been extensively harmonized. Using, Mun (2002, 139-146) definitions, the real option approach used in this thesis can be described as a non-closed form, binomial, recombining lattice, real options analysis assuming risk-neutral probabilities with volatility values received form a Monte Carlo Simulation.

Continuing, the data calculation ought to be ratified. Data collection was achieved directly from an existing wind farm in Burgenland, Austria. Using a data interface which directly accesses the turbines Supervisory Control and Data Acquisition (SCADA) system, the reliability, accuracy and authenticity of the data sets which form the basis of the modelling process are undoubtedly provided for. The electricity price estimations were gathered from an open-source internet source and compared with estimations from industry experts (Schmitt 2022). This price data was then revalued with inflation projections from the International Monetary Fund. Next, in order to accurately model the value of the existing plants the capture price of the turbines was calculated using historic price data form the publicly available auction results for the bidding group the turbines are located in. The capture rate proofed to be exceptionally high, due to the good wind site conditions. Again, a future model was applied, by replicating the capture rate expectations for Germany, which will experience a similar renewable energy expansion in the coming decade, as will be discussed later on. In order to adequately express future volatilities, the calculated capture price of the turbines was subjected to a Monte Carlo Simulation following a random walk logic to calculate concrete volatility factors.

Subsequently, the long-term historic wind measurement data form the existing wind farm is collected. The aforementioned SCADA System interface is capable of providing 10-minute average wind speed measurements for the whole running time of the turbines. This resulted in the wind profile calculation being based on nearly 550.000 individual measurements. These measurements are collected according to the industry standard Weibull curve basket system. With each measurement being allocated to a 1 m/s bin, which is then plotted from 0 m/s to the maximum achieved wind speed. Next the relative probability is calculated to give a better understandable indication of the wind profile. Additionally, the collected data is projected to the new turbine height using the wind shear formula following the logarithmic wind profile. Then, the influence of the technical degradation of the turbine is analyzed. Again using, actual turbine data form the SCADA System. Although, the influence of degradation will proof itself to be inconsequential it is necessary to validate it. Continuing, the wind measurements are overlaid with the power curve of a state-of-the-art turbine in order to provide an estimation on possible future revenues. Finally, the above defined real option analysis is performed and qualified in a result discussion. As mentioned above the owners and operators of approximately 400 turbines in Austria are now being put in front of the decision whether to repower or not. Realizing that these actors intend to pursue the most financially attractive path, adhering to the principles of the homo economicus defined by Eduard Spranger, the question arises at what point in time it is financially advisable to repower an existing wind farm, or, indeed, if it is at all (Spranger 1950, 148).

3.1 Real Option Theory

It is common practice in financial analysis to calculate the value of an investment by determining its Net Present Value (NPV). The NPV calculation methodology has a long history with Karl Marx referencing an early form as early as 1909 (Marx 1909, 4:548). Irving Fisher formalized the concept in 1907 in his work "The Rate of Interest" (Fisher 1907). A NPV calculation respects the time value of money, realizing that incoming cash flows lose value the further from present time they occur. The discount rate, or rate of return, is a pre-defined percentage, which increases with the risk of a default - it is the factor which is applied to the expected incoming cash flow. For illustration, let us assume that you lend a business partner € 99 and your partner promises you to pay you back € 100 in a month. This one-month long promise has a value of € 1. Now, what if your partner promises you to pay you back in, let's say, 5 years, suddenly, this deal becomes much less attractive for you as a lender, even though the promised return of € 1 stayed the same. The sole parameter that changed was the amount of time until payment – thus showing that money, besides its numeric value, also has time value.

Providing that values for incoming and outgoing cashflows over a certain period of time into the future, are either known or assumed, the following formula can be used to calculate the Present Value (PV) of an investment at a distinct point in time:

$$PV = \frac{R_t}{(1+i)^t}$$

Where t is the period in which the cashflows occurs, $(1+i)^t$ is the above-mentioned discount rate and R_t represents the net cashflow, meaning that negative (outgoing) cashflows have been subtracted from positive (incoming) cashflows. The sum of all net cashflows over all time periods (N) is thus the Net Present Value, resulting in:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

The beauty lies within its simplicity; however, this simplicity comes with the disadvantage that incoming cashflows as well as the discount rate are based on assumptions. Neglecting the negative impacts those assumptions might have, is a major issue in applying NPV-theory. However, this can be mitigated by including and calculating investment success probabilities, which will be applied within the forthcoming analysis of this thesis as well, however, in the context of a real options analysis. This is done using the Monte Carlo simulation method, which will be described in depth in the methodology section (Borison 2005, 8) Furthermore, a net present value calculation focuses on a Yes or No / Do or Don't situation. Either the investment is done, and cannot be reversed or it is never implemented. This is where Real Option Theory provides an insight into managerial flexibility.

Real Option Theory builds upon the logic behind so called financial options, which gives the entity that possesses such an option the ability to conduct a certain financial transaction at one point in time. This usually refers to the option to buy or to sell some market traded shares. A call option describing the right of purchasing a number of shares at a predefined price and time, or a put option describing the opposite and therefore selling such a security at some point in the future at a pre-defined price.

Another vital differentiation is concerned with the timing of conducting the option operation. On the one hand, so called American Options refer to options which can be executed at any point during the lifetime of the option. On the other hand, European style option transactions can only be performed at the exact pre-defined expiration date. The price of conducting such an option operation is called the exercise price, it is pre-defined and thus reflects the predictions of the option buyer and holder. One can also profit from the inherent value of the option and sell the option itself, at the so-called option price (Jordan 2011, 34–35).

A different approach to investment valuation is the so-called Real Options Analysis (ROA), which builds on the basic principles of the NPV calculation methodology but also incorporates the managerial flexibility which is not present in classic NPV formulas. Again, Irving Fisher, first discussed the issue of options, which decision makers have. However, only Stewart Myers reassessed the concept and keyed the now prevailing term of Real Options (Fisher 1930; Myers 1977). Even tough, ROA has now been used in financial academia as well as by practitioners over the past 40 years, misconceptions on the application of the various approaches which come with ROA have constrained the proliferation of the methodology. As Borison neatly put it in the Journal of Applied Corporate Finance in 2005:

This situation leaves potential practitioners in troubling circumstances. In principle, the concept seems valuable and appealing. But given the current state of practice, there is a good chance that one could either apply an unsound approach or make inappropriate use of a sound one (Borison 2005, 17).

In this article, Borison continues to argue that due to its dynamic nature and the manifold applicational variety, practitioners are required to be confident in knowing what they actually want to evaluate. It is vital for them to understand the problem they are faced with, in order to correctly identify a fitting real option approach.

An analysis of the various ROA approaches will be provided in the following paragraphs. Generally, in the case of investment making, a decision maker has various options during the period before, during or after an investment. Deciding to expand an existing investment, to abandon it, or to delay the decision on going forward with an investment would name just a few. Several Real Option models can be identified, including the options to (Mun 2002, 171–85)

- Abandon
- Expand
- Contract
- Wait
- Delay
- Choose
- Switch

Contextualizing, the option theory to wind farm repowering does mostly correlate with the option to wait on exercising the repowering or if seen from another perspective, the option to expand an investment which has already taken place in the past (Milovanović 2013, 18–19). Continuing with the wind energy framing, an option to abandon in the renewable energy sector, is likely to be present during the early project development phases. As early wind farm site analysis is not very cost intensive a project developer might go ahead and come to the assessment that due to freely available data certain plot of land provides itself for a wind farm. However, the developer is aware of the fact that due to political circumstances a privately developed project might not be feasible due to resistance from local actors. Thus, after securing the land plots the developer has the option to abandon the project and sell of the land lease agreements to a publicly owned and/or municipally controlled entity etc.

The expansion option is easily graspable and actually one of the most common options in the renewable energy sector, as realized projects are often downsized to minimize the impact on the local population due to hesitance of the locals. Now, after some years of unproblematic and economical operation, the publics opinion on the site turns positive, as jobs have been generated and, in some cases, PPAs with the municipality have resulted in an electricity price drop for the local population. Thus, the operator of the wind farm now has the option to expand the existing wind farm with more turbines, as there will not be as much resistance from the public anymore. The real option analysis method would now compare dynamic cash-flows based on pre-defined variables of the existing plant and the expanded plant. This case is indeed very similar to that of the repowering case, however in repowering, some timing aspects are different, as maintenance contracts expire and turbines close in on their expected end of life time.

In our case, a repowering scenario is a combination of the option to expand as well as the option to continue with existing production or waiting until a favorable market situation arises. Deciding on which option to choose simply is a maximization between each calculated option value at each calculated point in time.

Identifying why Real Options are a powerful tool in financial decision-making processes revolves around the revelation that most financial decision are not based upon a single yes/no decision but are rather based on multiple decision triggers which also tend to change and evolve as time progresses. Mun (84-85) shows this in a compellingly simple example, which subsequently has been adapted to a wind energy relatable scenario but using the well put explanations of Mun. The example intends to develop on the concept of optionality in decision making, focusing on simplicity as it is initially important to understand optionality itself. The example, which uses Muns analogies, shall be described more closely in the following paragraphs.

In order to move forth with the example, two important factors have to be defined; the Weighted Average Cost of Capital (WACC) as well as the risk-free rate *rf*. Both are factors which are applied to the free cashflows, however, the WACC shall be used as the discounting factor for incoming (i.e. returns) and the *rf* for the outgoing cashflows (i.e. investments). This is due to the fact, that the WACC represent market risks, under which the incoming cashflows operate and the *rf* is used for the investment which is classified as a private risk.

Variables with market risks should be discounted at a market risk-adjusted rate, which is bigger than the risk free rate, which is used to discount variables with private risks (Mun 2002, 61)

Assuming that a € 100 million investment in new turbine components, or, for example, the installation of a new substation that enables the farm to feed in more electricity, increases revenues in such a way that after one year electricity sales will create € 120 million, at a 15 percent weighted average cost of capital and a 5 percent risk free rate. This results in an NPV of € 4.3 million according to the following Figure 5. Mun describes the process as follows:

The […] example provides a simplified analogy to why optionality is important and should be considered in corporate capital investment strategies. Suppose you have an investment strategy that costs [€] 100 to initiate and you anticipate that on average, the payoff will yield [€] 120 in exactly one year. Assume a 15% [WACC] and a 5% risk free rate […]. As Figure [5] illustrates, the [NPV] of the strategy is [€] 4.3, indicating a good investment potential because the benefits outweigh the costs (Mun 2002, 83–84).

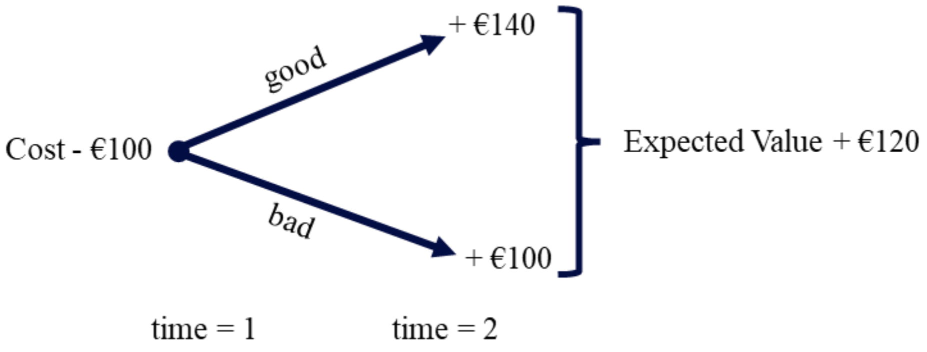
$$\text{Net Present Value} = \frac{120}{(1.15)^1} - 100 = € \, 4.3$$

Figure 5: Simplified NPV Scenario (Mun 2002, 84)

Now, assuming that the investment is not undertaken at time = 0, but the decision makers rather decide on postponing the investment until time = 1, a good electricity market will have provided cashflows at € 140 million and a bad market of € 100 million, as depicted in the following Figure 6 with an expected value of € 120 million which is the average of between the good and bad scenarios. Mun describes the process in Figure 6 as follows:

[…] [I]f we wait and see before investing, when uncertainty becomes resolved, we get the profile shown in Figure [6], where the initial investment outlay occurs at time one and positive inflows are going to occur only at time two. Let's say […] the

average or expected value came to be [€]120 with good market demand providing [€] 140 cash flow and in the case of bad demand, only [€] 100 (Mun 2002, 84).



$$\text{Net Present Value} = \frac{140}{(1.15)^2} - \frac{100}{(1.05)^1} = €10.6$$

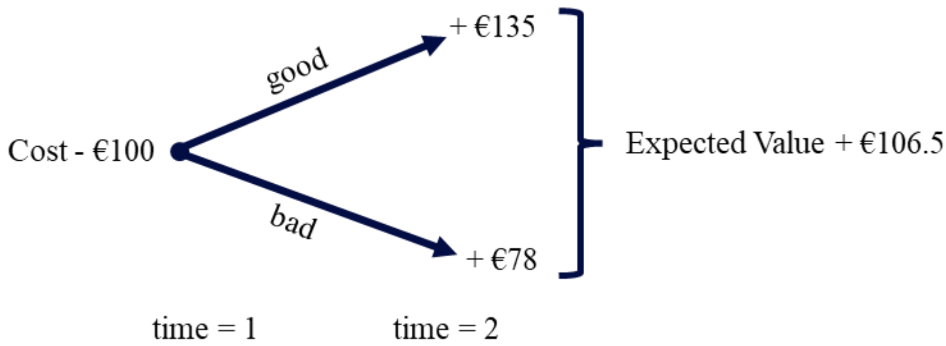
Figure 6: Adding Uncertainty and Optionality (Mun 2002, 84)

Thus, not investing immediately at time = 1, even if the market did indeed act favorably and achieved the expected NPV of € 120, does have an intrinsic value, as can be seen in the figure above. This is due to the fact that with a current NPV of € 120 the good market option now enables us to make € 140 whilst the bad scenario only creates € 100, directly offsetting the € 100 investment costs. Thus, the cumulative Net Present Value, adds up to € 10.6. Comparing that with the initial classic NPV view, shows that this flexibility has a value of € 6.3, again, reflecting upon Mun's conclusions:

If we had the option to wait a year, then we could better estimate the trends in demand and we would have seen the payoff profile bifurcating into two scenarios. Should the scenario prove unfavorable, we would have the option to abandon the investment because the costs are identical to the cash inflow (-[€] 100 versus +[€] 100), and we would rationally not pursue this avenue. Hence, we would pursue this investment only if a good market demand is observed […], and our [NPV] for waiting an extra year will be [€] 10.6. This analysis indicated a truncated downside where there is limited liability because a rational investor would never knowingly enter a sure-loss investment strategy. Therefore, the value of flexibility is [€] 6.3 (Mun 2002, 84).

However, this option to wait does come at cost of an exemplary € 5 as you are denying yourself the option of achieving cashflows form an earlier point on.

Additionally, it has to be considered that not investing at year = 1 or even year = 0 results in no incoming cashflow for those two intervals. Accounting for those factors a bifurcation of opportunity according to the following Figure 7 can be expected:



$$\text{Net Present Value} = \frac{135}{(1.15)^2} - \frac{100}{(1.05)^1} = €6.8$$

Figure 7: The Cost of Holding the Option (Mun 2002, 85)

Mun describes this final step as follows:

> *[…] [A] more realistic payoff schedule should look like Figure [7]. By waiting a year and putting off the investment until year two, you are giving up the potential for cash inflow now, and the leakage or opportunity costs by not investing now is the [€]5 less you could receive ([€]140 - [€]135). However, by putting off the investment, you are also defraying the cost of investing in that the cost outlay will only occur a year later. The calculated net present value in this case is [€]6.8* (Mun 2002, 85).

3.2 Literature Review and Current State of Research

As has been said, the concept of managerial flexibility in the context of options has been analyzed by Irving Fisher as early as 1930, with Stewart Myers focusing on so-called Real Options in 1977. The energy sector has great potential for the application of real options as it is subjected to a high-risk environment in which the value of options becomes greater (Ritzenhofen and Spinler 2016, 76–79). Thus, there has been extensive research in the energy as well as commodity sector of real options analysis as the industry provides itself for such undertakings.

An early example for a real options approach to a commodity business such as copper mines is provided by Brennan and Schwartz who assessed the financial feasibility using stochastic price developments (Brennan and Schwartz 1985). In the same year McDonald and Siegel approached the issue of options investment from the perspective of a monopolized plant owner who's commodity price follows a stochastic movement and who has the option to shut down operations to evade unfavorable economic phases (R. L. McDonald and Siegel 1985). In the following year, again McDonald and Siegel, published a paper in which they evaluate the option of waiting to install a synthetic fuel plant in an risky environment (R. McDonald and Siegel 1986). In 1986 Paddock, Siegel and Smith build upon the work of the previous authors in the field and point out the importance of raising real options away from financial option methodology especially in regards to market equilibria in the stock of the underlying asset (Paddock, Siegel, and Smith 1988).

In the following decades the field of research on real options and their application in the real world has massively expanded. Some notable papers focusing on the application in the field of (renewable) energy include but are not limited to the following compilation. Ritzenhofen & Spinler assessed the influence of subsidy regimes on renewable investments, using a pentanomial lattice real option approach. The pentanominal lattice approach is similar to the approach used in this thesis as they both rely on the concept of lattices. The difference being that, in a binomial lattice a single source node disperses, as the name suggests, into two possible outcomes, where as a pentanominal lattice node has five individual outcomes. This increase in granularity results in greater precision, however also results in a massive additional computational effort.

Ritzenhofen & Spinler compare the NPV of projects in feed-in-tariff schemes with investments under a free market regime, arguing that, due to high uncertainty in price development, the free-market scenario provides itself to be analyzed using a real option approach (Ritzenhofen and Spinler 2016). Nadarajah et al. dedicated a section of a 2017 article to a compelling scenario for using the real options approach in the energy sector. More precisely, they considered a natural gas storage scenario in which real options are used to determine return estimations. This approach using various least squares Monte Carlo methods provides itself to be adapted to battery electricity storage (Nadarajah, Margot, and Secomandi 2017). Himpler & Madeler used an optimal stopping problem approach with thresholds to determine the optimal time for repowering, assessing probabilities with a Monte Carlo Simulation (Himpler and Madlener 2014). Realizing the perceivable gap between academic approaches and real world business applications, Locatelli, Mancini & Lotti try to demystify real option valuation in the energy sector by providing a guide to using real option methodology to successfully define investment thresholds (Locatelli, Mancini, and Lotti 2020).

3.3 The Tool: Model Development

Creating any software tool which will be used by practitioners who are not necessarily affiliated with the intricate methodology behind such a system can be viewed as a pedagogical task. The creator has to convey the knowledge and insights gained by the software analysis in such way that users can easily deduce the results to real world decisions. The most intricate tool, with the most in-depth analysis is basically useless to a corporation, if the only one who can interpret the results is the creator of the software him or herself, which in most cases is not in a managerial, final decision-making position. Thus, a not negligible part of real-option analysis is communicating the results and what they actually mean to decision makers.

Besides result interpretation and communication, a second important factor to consider when creating any software tool, is input adaptation. Meaning that, for example in the case of this thesis, the input parameters should be made adaptable in order to adhere to changing market environments. This is to say that, in this case, the value of the tool increases if it can be used for more than one specific case. Therefore, it ought to be made clear, which parameters and what input data has to be adapted in what way to cater for new project evaluations. For this it provides itself to create a text document, similar in its structure to a handbook, which guides the user through the steps of data preparation. Here a classic caveat applies: increasing the complexity of the model also increases the needed savoir-faire of the applicant, and conversely also creating the possibility of unwanted anomalies due to applicational errors. Basically, meaning that the probability of errors increases with inherent tool complexity (Mun 2002, 171–85).

As previously stated, the value of such a tool increases with the number of times it can be successfully applied to varying projects. Successfully, meaning that no mismanagement and erroneous decision making originated from the interpretation of the tools results. Here the aforementioned tool complexity comes into play; in many cases a simpler tool, with lower accuracy has more intrinsic value to a corporation as internal decision making is less likely to be based upon flawed business intelligence. Additionally, in the managerial business decision process, the real option analysis stands at the very beginning of the decision-making process. Here we have an idea, in our case an option, which might proof to be financially favorable to our company. Thus, a real option analysis is made to give an insight into its financial viability. This first, analysis is likely to be based on assumptions. These assumptions have to be continuously reviewed, verified and adapted with more precise data from financial or engineering consultants. It would be foolish to blindly follow a first analysis, reinterpretation and clarification of the case at hand have to be constantly integrated. Again, highlighting the importance of transparent input data reprocessing for ease of use (Wendt 2023).

In the case of this thesis the most vital input data points are the electricity price estimations and historic production values of the existing wind farms. The applicant of the tool has some possibilities in adapting the input data. Firstly, it is advisable to adjust the monthly electricity market estimations, as time progresses with the actually achieved market prices. This gives an indication as to whether or not the initial estimations proofed to be reliable as well as decreasing the volatility and therefore increasing estimation precision. Concerning the wind speed data which is used in the analysis, it is advisable to continuously add newly measured data to the tool. With an already existing measuring time of nearly 10 years, it is unlikely that the newly data will change much in terms of the wind profile, however the technical availability becomes more and more interesting the closer the turbines come to their expected end of lifetime.

4 Key Input Parameters

The following Table 1 and Table 2 express the key input parameters for the existing wind farm and its 'would-be' repowered configuration. A discussion of the most vital economical parameters will be presented as well.

Table 1: Existing Wind farm

Wind Turbine Generators (WTG):	23
Installed Capacity [MW]:	69
Turbine Capacity [MW]:	3
Production per WTG and Year [MWh]:	146.000
Investment Cost per WTG:	€ 3.100.000
Operation and Maintenance Costs per WTG and Year:	€ 155.000
Discount Rate:	10%

Table 2: Repowered Wind farm

Wind Turbine Generators (WTG):	21
Installed Capacity [MW]:	153,3
Turbine Capacity [MW]:	7,3
Production per WTG and Year [MWh]:	246.450
Investment Cost per WTG:	€ 11.096.000
Operation and Maintenance Costs per WTG and Year:	€ 205.375,03
Discount Rate:	10%

The existing wind farm, consisting of 23 turbines at 3 MW each, produces on average 146.000 MWh of electricity per year. If repowered, the number of turbines has to be decreased by approximately 10% (see section 2.2) resulting in 21 turbines at 7,3 MW each. The power curve of this exemplary turbine will be displayed in section 4.5. The cost of the turbines as well as the operation and maintenance costs of the existing wind farm have been gathered from literature. This is due to the satisfactory historic price data in the literature (Hau 2016, 914; 920). Due to the highly dynamic price situation in the market today, the values for the repowered wind farm have been gathered from a recent report, which will be closely examined in Section 4.1. Lastly, the stated discount rate can be considered as conservative at a value of 10% (IRENA 2022, 181–83).

4.1 Current Investment and Operation & Maintenance Costs

Concerning the issue of investment costs this thesis relies on the results of the report on the current subsidy scheme in Austria. The report was commissioned by the Ministry for climate protection, environment, energy, mobility, innovation and technology which is responsible for the subsidy scheme (Resch et al. 2022, 8). The report considers the investment costs to be the capital expenditure necessary to purchase the turbines as well as the costs associated with grid access (Resch et al. 2022, 134). The report was chosen to be representative for this thesis due to its recent publishment, its focus on Austria as well as its relevance for the subsidy scheme under which the repowered turbines will operate. Furthermore, the report considers the recent market dynamics which resulted in drastic increases in investment costs (Resch et al. 2022, 66–69). The values gathered from the report where subsequently adjusted for inflation according to the model in Figure 7 and dynamically included into the Real Options Analysis.

In general, the report identifies a degressive trend in investment costs for wind energy over an observation period from 2014 until 2019, resulting in mean investment costs of 1.552 €/kW. Continuing, the authors decided on focusing on the data sets of the year 2018 to generate representative values, which resulted in mean investment costs of 1.507 €/kW. As mentioned above, grid costs have to be added to this value, resulting in a representative, mean investment cost value of 1.520 €/kW (Resch et al. 2022, 133–34). As this is the most recent average value, this thesis will make use of this value for its dynamic calculation. With an estimated new capacity of 153,3 MW total, a capital expenditure of 11.096.000 € per turbine totaling in 233.016.000 € for the whole wind farm of 21 turbines can be expected. Concerning the topic of O&M costs, the authors identified a mean value of 18,2 €/MWh over the whole observation period as well as a representative value of 17,5 € when focusing on plants that went into operation in the year 2018 (Resch et al. 2022, 136–37). For ease of comparison with the values of the existing wind farm, these values are adjusted to cost per turbine and year, by multiplying the yearly production (which will be calculated in Section 4.5) with the mentioned per MWh value and then dividing the total costs of O&M by the number of turbines resulting in a value of 205.375,03 € per turbine and year.

4.2 Sale of Electricity

Now, in order to adequately estimate future earnings from a renewable energy source it is vital to realize that the average electricity price model will not reflect possible earnings from a renewable electricity source. This is due to the phenomenon of market cannibalization. Market cannibalization refers to the effect of significant, simultaneous production of renewable energy sources, especially wind and PV. If a market zone experiences high renewable production due to overall sunny and, or windy conditions, renewable production will skyrocket (Jones and Rothenberg 2019). Evidently, increasing supply in such a manner will logically result in plummeting prices, as the demand does not keep up with production and storage capabilities are limited. An extreme form of such a market situation are negative prices. This is to show, that renewables do not typically achieve the estimated average electricity price, such as baseload contracts would do, but rather prices at much lower levels. To compensate for that, electricity price models for renewable energies account for this phenomenon and aim to give an estimation of the price which each renewable source will be able to achieve, this price is the so-called capture price (Liebensteiner and Naumann 2022, 4).

An often-used model to give an indication on the long-term development of assets which are in one form or another bound to a liberated market is the geometric Brownian Motion (GBM). GBM has several benefits such as its relatively simple application, path independency, and historically proven accuracy. However, the main issue with GBM is that it assumes volatility to be constant and that it cannot incorporate difficult to predict market situations and high fluctuations in short periods of time. This becomes especially relevant when analyzing electricity prices in the light of COVID-19 and the Russian invasion of Ukraine. Prices have reached unforeseen heights, which are estimated to normalize (decrease) over the coming years. However, a constant average reduction of prices in the foreseeable future does not correlate to a GBM (Ibe 2014, 308–9). Thus, it is necessary to adapt estimations. For this thesis the following baseload price projections for the average baseload price for the EU27 as well as Switzerland, Norway and the United Kingdom, which will also be adjusted for inflation, are used (Schmitt 2022).

Table 3: Average Baseload Price for EU27

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
High	180 €	125 €	100 €	95 €	90 €	85 €	82 €	80 €	83 €	86 €
Central	145 €	100 €	90 €	85 €	80 €	75 €	72 €	70 €	70 €	70 €
Low	130 €	90 €	80 €	70 €	65 €	60 €	55 €	50 €	51 €	52 €
	2033	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**
High	89 €	92 €	95 €	97 €	99 €	100 €	102 €	100 €	101 €	102 €
Central	71 €	71 €	72 €	71 €	70 €	71 €	72 €	70 €	71 €	72 €
Low	53 €	54 €	55 €	56 €	57 €	59 €	62 €	60 €	61 €	62 €
	2043	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**		
High	103 €	104 €	105 €	107 €	109 €	111 €	113 €	115 €		
Central	73 €	74 €	75 €	76 €	77 €	78 €	79 €	80 €		
Low	63 €	63 €	65 €	67 €	69 €	71 €	73 €	75 €		

Concerning inflation, historic values, specific for Austria, as well as projections up until 2028 from the International Monetary Fund have been used as a base to extrapolate inflation assumption up until 2060. For the years after 2028 the yearly average Austrian inflation from 1988 to 2020 has been used to adapt future financial obligations, especially the operations and maintenance costs (see Figure 8) ("Report for Selected Countries and Subjects" n.d.).

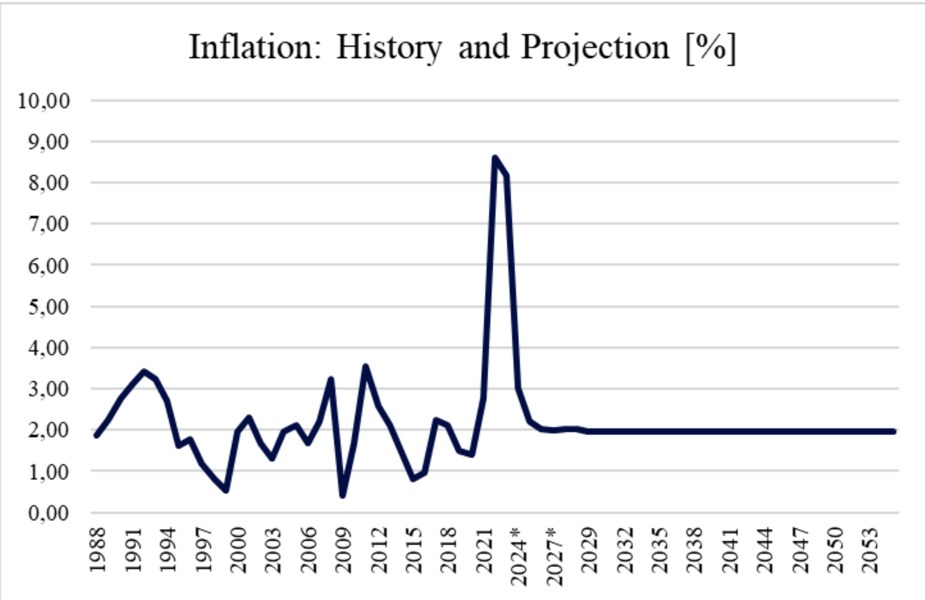


Figure 8: Inflation: History and Projection

As the capture price is a site-specific identifier, the capture rate of the installed power plants shall be calculated as well. In order to do so, the production data of the turbines in 10-minute intervals for the past four years is cross referenced with the 15-minute day-ahead electricity prices of the bidding group in which the turbines are located for the same years. Due to the difference in interval the hourly average was calculated. Then, by dividing the total calculated revenue with the sum of the production the average capture price over each specific year is defined. By dividing the capture price with the average baseload price, the capture rate at which the plants have performed is defined (see Table 4 below) (Blume-Werry et al. 2021, 231–33).

Table 4: Capture Rate

2019	2020	2021	2022	2019-2022
1	0,93	0,98	0,91	0,95

Comparing the historic capture rates of the wind power plant at hand shows that this plant performed favorably in comparison to a comparable market such as that of Germany. However, the capture rate is expected show a downward trend, due to the increase of wind power capacity (Blume-Werry et al. 2021, 233). Therefore, a linear degression approximating the values of Blume-Werry et al. but incorporating the obviously capture-rate-favorable site that the historic data has shown, will be used as a multiplication factor (see Figure 9).

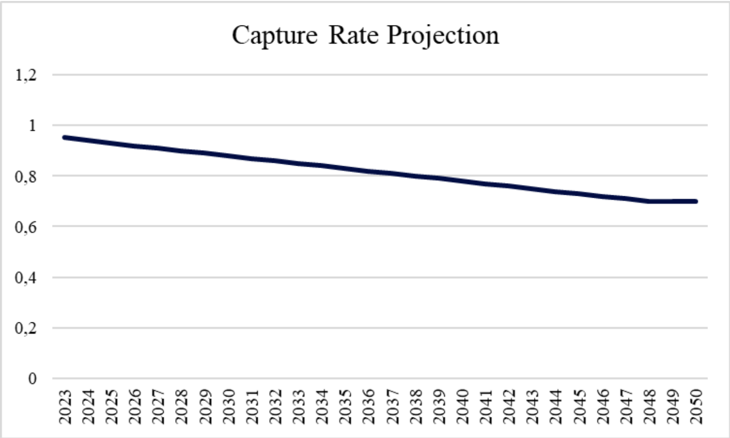


Figure 9: Capture Rate Projection

The conservative capture rate forecast approximated above is used as a multiplication factor for the baseload prices which have been listed above resulting in the following wind capture price forecast for the specific site at hand which has also been adjusted for inflation according to the previous paragraph. The three lines represent the low, central and high scenarios.

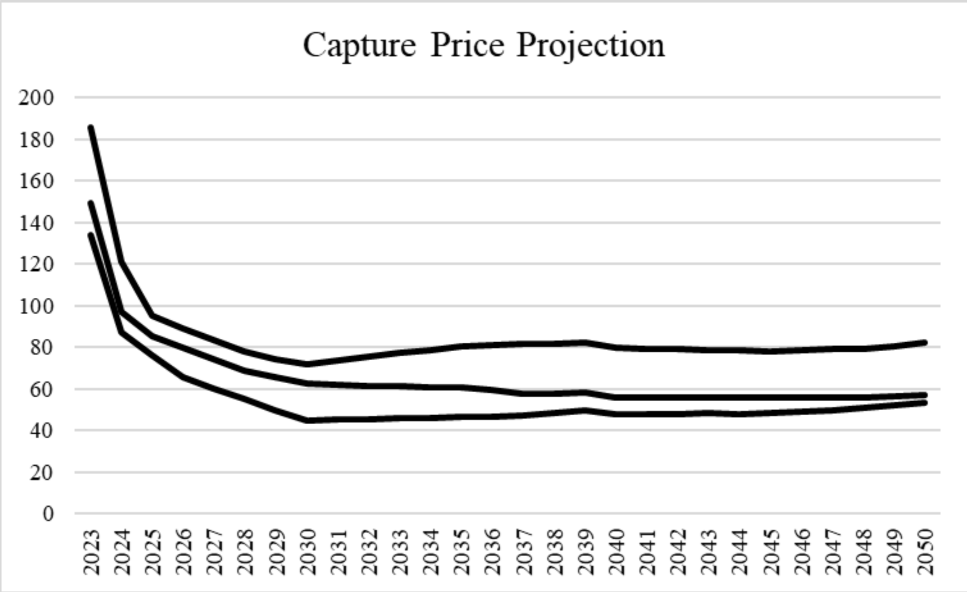


FIGURE 10: Capture Price Projection

In order to receive the necessary information on the volatility, the underlying onshore wind capture price data is used to perform a Monte Carlo Simulation (MCS) using EXCEL and the following random walk logic. First, a random value between the Low and High scenario of each year using the RANDBETWEEN function is defined and repeated 500 times for every year, see TABLE 5.

TABLE 5: Exemplary Illustration of MCS in EXCEL

	2024	2025	2026	(…)	2060
Simulation 1	=randbetween(323;109)	=randbetween(335;97)	=randbetween(276;89)	(…)	=randbetween(164;74)
Simulation 2	=randbetween(323;109)	=randbetween(335;97)	=randbetween(276;89)	(…)	=randbetween(164;74)
Simulation 3	=randbetween(323;109)	=randbetween(335;97)	=randbetween(276;89)	(…)	=randbetween(164;74)
(…)	(…)	(…)	(…)	(…)	(…)
Simulation 500	=randbetween(323;109)	=randbetween(335;97)	=randbetween(276;89)	(…)	=randbetween(164;74)

As the yearly development of the prices is of interest, the yearly change in prices is calculated by dividing each year with the next. Next, the standard deviation using the STDEV function of Microsoft EXCEL for each of the 500 simulations is calculated. Subsequently, the average over all simulations is calculated. The STDEV function is based on the formula of the natural logarithm's standard deviation defended as:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x-\bar{x})^2}$$

which can also be adjusted for varying intervals using:

$$\sigma(T_2) = \sigma(T_1)\sqrt{\frac{T_2}{T_1}}$$

The above-described average of all 500 standard deviation simulations is the volatility of the onshore wind capture prices, which has been calculated to be 0.33. This calculated volatility will be used in the Binominal Tree Real Option Analysis in section 5.2.

Lastly, the electricity prices achieved on the free market have to be adjusted by the subsidy scheme under which the plants operate. For the non-repowered plant, it is assumed that – as most renewable producers did – the plant left the Feed-in Tariff subsidy scheme and proceeded to sell the produced electricity on the free market. However, the operators have the choice to reenter the Feed-in Tariff if they want to do so. Thus, it is assumed that for the non-repowered plant, the electricity is sold on the market as long as the price is above the fixed tariff. If the price drops below that value, the plant reenters the subsidy scheme and proceeds to receive constant earnings at € 97 per MWh according to the ÖSG 2012 (i Magazin 2022; *Ökostromgesetz 2012 - Bundesrecht Konsolidiert, Fassung Vom 01.06.2023* 2012).

The repowered plant would operate under the rather newly established Erneuerbaren Ausbau Gesetz which follows a floating / sliding market premium model. Thus, a price is set in an auction, where operators bid the value with which they can financially feasibly operate the plant. However, if the market price is higher than this set value, the operators receive the market price (Resch et al. 2022). It must not be forgotten that there is a cap implemented in the legal framework, which requires the wind farm owners and operators to return 66% earnings if the achieved market price crosses a certain threshold (*Erneuerbaren-Ausbau-Gesetz - Bundesrecht Konsolidiert, Fassung Vom 04.06.2023* 2023). A visual comparison of the most common types of subsidy schemes can be seen in Figure 11 (Banja et al. 2017). As said above, the "Feed-in-Tariff" might apply to the existing plant and the "Sliding Feed-in-Premium" would apply to the repowered plant.

Figure 11: Subsidy Schemes

For the sliding feed in premium system, it is also necessary to incorporate the site-specific adjustment, which basically adds or subtracts a certain amount from the subsidy price according to the value of the site. Meaning that a good wind site receives less subsidies and a site which is less attractive receives more. As the price is set in an auction, the highest possible bidding price is used as a guideline for our price-design, which currently stands at 82.2 € per MWh. This value was received from an online calculator by Oesterreichs Energie, which is publicly available. Again this value will form the base of the price, lower market values are not regarded but rather replaced by said value (Oesterreichs Energie 2022).

4.3 Wind Resource

The second relevant factor to calculate the earnings of the wind farm repowering project is the wind speed at the new turbine height. Conveniently, as a wind farm has been operating at the intended site for several years, it is possible to use the measured historical wind speed data of said wind farm to model the wind speed for the repowered wind farm. This is done using the 10 min average meter per second wind speed data going back 10 years. It is important to realize that calculating the average wind speed over this period of time, might provide an initial indication of the attractiveness of the site, however it is additionally necessary to analyze the distribution of different windspeeds occurring. In order to cater for this need, the average 10 min wind speed of each measuring point (i.e. turbine) has been calculated. To illustrate the windspeed distribution, it is calculated how often a certain wind speed is reached. This is usually done in one meter per second steps, resulting in the following illustration:

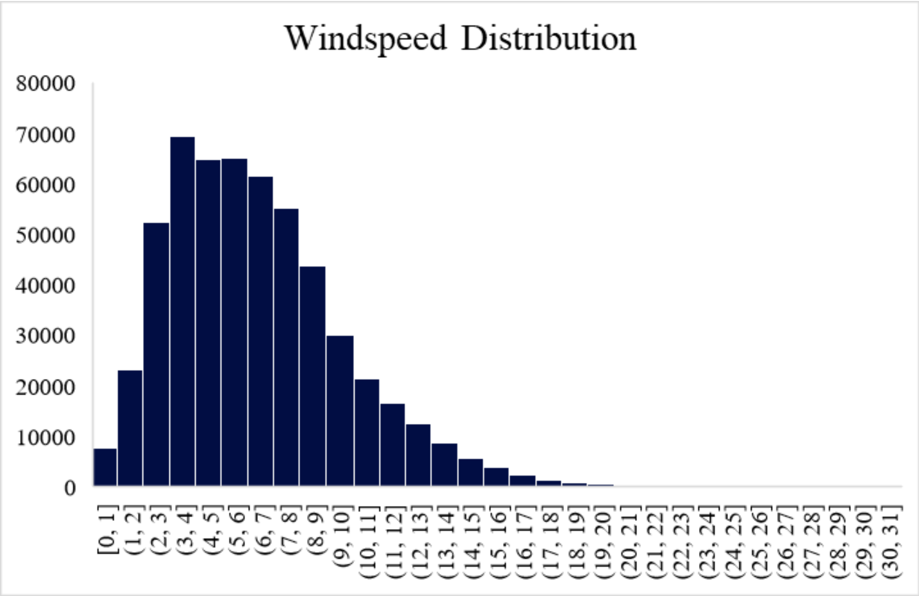


Figure 12: Windspeed Distribution

This example includes 546.752 10-minute average values, approximating a measuring horizon of nearly 10 years. When working with wind speed data measured from turbines it is important to differentiate between actual measured windspeed of 0 m/s and the turbine reporting 0 m/s due to a system failure. As such failures do occur, it is not possible to receive data for every 10-minute interval of the past decade. Thus, explaining why the sum of all absolute probabilities is not equal to 10 years divided by 10 minutes. It can be seen that the most often measured wind speed is somewhere between 3-4 m/s. This value is the absolute probability of a wind speed between 3-4 m/s.

Figure 13 shows that, naturally, yearly divergences in the wind speed distribution do occur, however taking the average windspeed over 10 years sufficiently approximates the risk for the use in this thesis. To incorporate higher risk scenarios, it is of course possible to choose more conservative values.

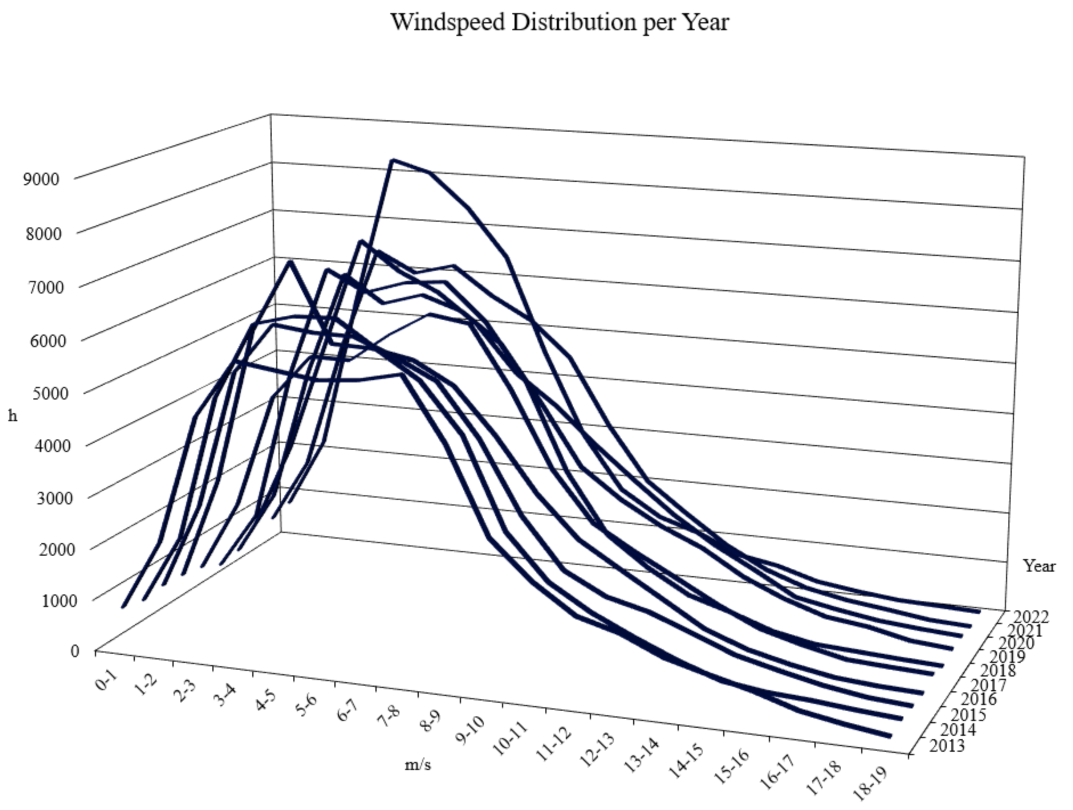


FIGURE 13: Windspeed Distribution per Year

In order to gain a different insight into these hard values it is recommended to calculate the relative probabilities which are the percentages of each windspeed occurring. This is done by dividing the absolute probabilities with the total number of all measuring points. Resulting in the distribution visualized by FIGURE 14.

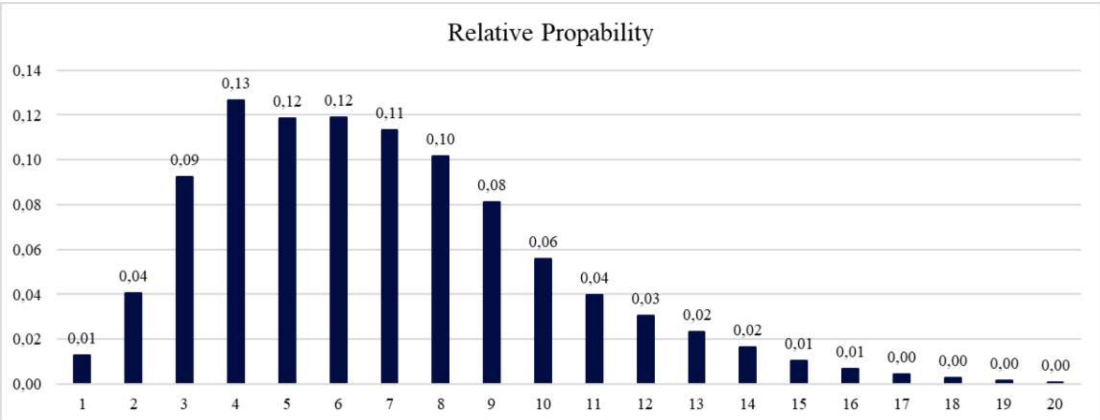


FIGURE 14: Relative Probability

Having qualified and analyzed the existing wind measurement data, the next step is to incorporate the influence of the wind shear phenomenon into our energy yield estimation as the nacelle height of the repowered turbines will be greater than that of the installed plants. Wind shear refers to the correlation of increase in height and increase in wind speed, this is commonly referred to as the logarithmic wind profile with the following formula:

$$\overline{v}_H = \overline{v}_{ref} * \frac{ln\frac{H}{z_0}}{ln\frac{H_{ref}}{z_0}}$$

Where $\overline{v}_H$ is the average windspeed at height H in meter per second. $\overline{v}_{ref}$ refers to the reference, so the measured windspeed of the existing turbines in meter per second. Furthermore, the natural log with base e = 2.7183, the reference Height H_{ref} (which is again the height at which the measured wind speed data originated from) as well as the new nacelle height at H meters, are used to perform the calculation. The final vital parameter is z_0 which is a numerical terrain description focusing on the roughness length. The lower the value the flatter the terrain is. Open water surfaces with no obstacles in around a five-kilometer radius are described with a roughness length of around 0.0002. At the other end of the scale, dense urban environments with high rises and sky scrapers and a roughness length of 1.6 can be found. For the repowering project at hand, a typical eastern Austrian wind farm site which is located in a mainly agriculturally used land environment, with little to no trees and buildings, resulting in a roughness length of 0.03, is used. Assuming that the original nacelle height is 135 meters and the new turbines will have a tower height of 175 meters, a higher average wind speed over the whole observation period of 0.22 meters per second, can be observed (Hellmann 1914).

4.4 Technical Availability

Another important factor when considering the cashflow of the underlying asset is the technical availability of the plant and how it might influence earnings due to a decrease in performance or even total failure of the technical system. For this the historic data of the wind farm at hand is analyzed.

When speaking of availability in the context of wind power turbines, there generally are two measuring practices which can be applied. Firstly, the so-called technical availability which is measured in time and secondly the energetical availability which focuses on the lost electrical energy. The energetical availability is the ratio between the actually produced electricity versus the electricity which could have been produced if the turbine was running optimally. Thus, if the turbine experiences some form of malfunction during a period of high wind this malfunction will have a more negative effect on the ratio than a failure to operate during a less windy section of the day. For comparison reason, however, a measurement which focuses on actual time of standstill and/or malfunction gives a better indication on the overall evolution of the availability of the plant. Thus the technical availability of the wind farm will be used as the basis for the following analysis (Fördergesellschaft Windenergie und andere Dezentrale Energien 2017, vii). The database of the wind farm at hand provides monthly averages on the technical availability in decimal percentages over the past ten years.

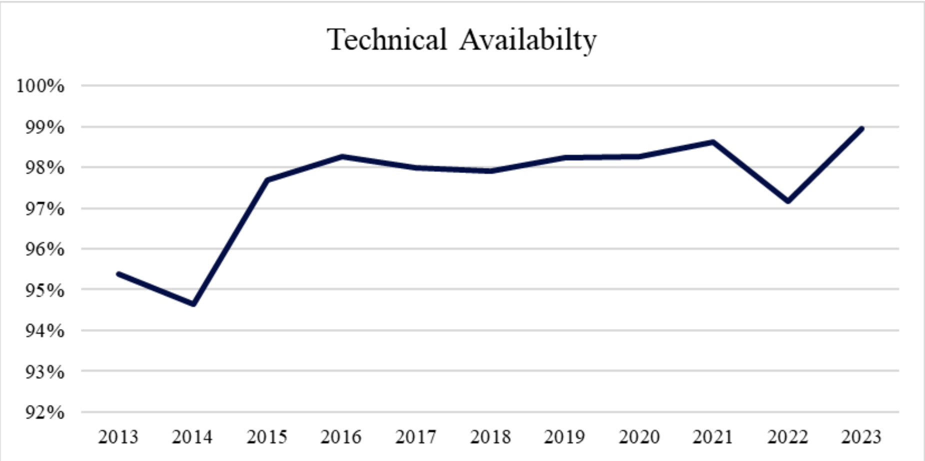


Figure 15: Technical Availability

As can be seen in Figure 15 after achieving full operation of all turbines in 2014, the technical availability of the plants revolved around 98% for nearly 7 years, dropping to its all-time low of just above 97% in 2022. The year 2022 might give an indication that due to the aging of the turbines the availability is beginning to suffer, however as 2023 was the best year in terms of availability so far, this conclusion might prove itself to not hold up for the coming years.

Acknowledging the not measurable degradation of the turbines, a decrease in technical availability will not be incorporated in the model, as the data does not call for a consideration of the issue. Additionally, some wind farm operators might choose to close a full-service contract with the turbines manufacturer. Such a service contract often includes some form of reimbursement for losses in revenue due to a malfunctioning turbine, making a revenue based appraisal of technical availability not as necessary (Hau 2016, 916–17).

4.5 Electricity Production

Classifying the wind energy potential of the site plays a vital role in deciding on which turbine to install. As modern wind turbines achieve their nameplate capacity at a certain wind speed range, the data on how many times what wind speed is achieved is vital to provide an estimation on what production can actually be expected. This is why turbines manufacturers provide a wide array of different turbine types for different wind classifications, as a turbine which is built for a typical onshore site with an average 5 m/s Weibull distribution (similar to the distribution used in this thesis) will vary significantly from a turbine which experiences a constant 8 m/s at an off-shore site. Figure 15: shows a typical power curve for a state of the art 7,3 MW wind turbine.

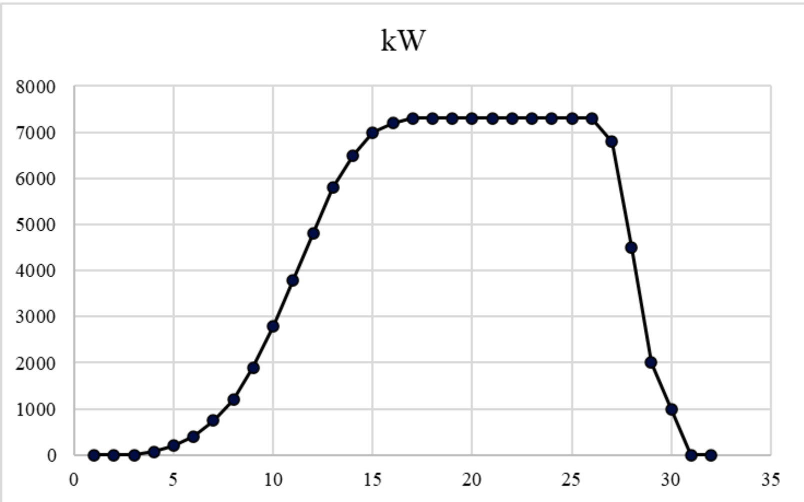


Figure 16: Power Curve

As Figure 16 shows, this exemplary turbine starts producing at a wind speed of around 3.5 meters per second, achieving its nameplate capacity at 17 m/s. At 26 meters per second the turbine starts to curb its production and stopping its production at 31 meters per second to avoid storm related damages. Now, in order to estimate the yearly production of this turbine at our site, the power curve is cross referenced with the wind distribution by multiplying the relative probability of each wind speed with the production capacity in kW at said windspeed times 8,760 hours in the year. The following graph shows the distribution of production. In total a production of 11,735.72 MWh per year can be expected (see Figure 16).

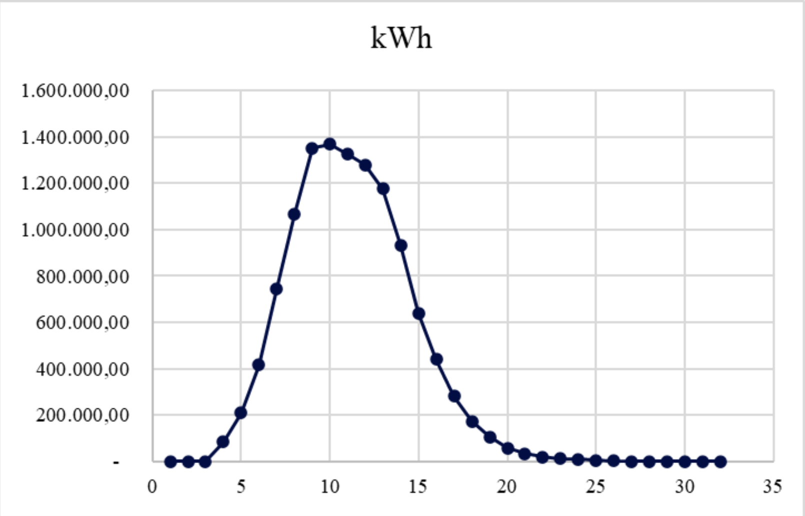


Figure 17: Production Curve

Using the two production data sets which have been calculated in the previous section, it is now possible to create the underlying financial models in the form of discounted cash flow calculations. Using the formulas outlined in Section 3.1, the data points outlined in Table 1 and Table 2 as well as the necessary information on inflation, which has been presented above, the Present Value (which is the sum of the nominal cashflows) of letting the not repowered plant run for the next 5 years (until the expected end of lifetime) is calculated to be 57.672.057 € (see Table 6).

Table 6: Present Value Calculation for Existing Wind farm until End of Lifetime

	Year 1	Year 2	Year 3	Year 4	Year 5
Discounted Costs	-3.904.175 €	-3.618.461 €	-3.353.655 €	-31.082.29 €	-2.880.763 €
Revenues	22.271.714 €	14.412.766 €	14.438.159 €	14.438.159 €	14.438.159 €
O&M	-4.294.593 €	-4.378.337 €	-4.463.715 €	-4.550.757 €	-4.639.497 €
Nominal Cashflow	17.977.121 €	10.034.428 €	9.974.444 €	9.887.402 €	9.798.662 €
Discounted Cashflow	16.342.837 €	8.292.916 €	7.493.947 €	6.753.228 €	6.084.198 €

5 Results

Lastly, by applying the laid-out methodology to approach the objective stated at the very beginning of this thesis, it was possible to achieve valuable results, which ought to be discussed in the following sections.

5.1 Capture Prices for Wind Power

For sake of completeness, the above calculated site-specific capture price shall be reintroduced to provide the whole, concise picture of the main dynamic input parameter which was calculated in this thesis. Historically speaking, the wind farm at hand proofed itself to be capture rate beneficial. Achieving a capture rate of approximately 0,954 in the years of 2019 until 2022 (see last cell of Table 4). Furthermore, the last wind park capture rate which can be calculated from historic data was taken as a starting point for an extrapolation into the future The extrapolation showed a decrease from 0,95 in 2023 to approximately 0,70 until 2050 (see Figure 9). Finally, the site-specific capture rate was used as a multiplication factor for the underlying energy price model, resulting in the following concrete capture price values.

Table 7: Result of the Capture Price Calculation

	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
High	186	121	95	89	84	78	74	72	74	75
Central	150	97	86	80	74	69	65	63	62	61
Low	134	87	76	66	60	55	50	45	45	46
	2033	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**
High	77	79	80	81	82	82	82	80	79	79
Central	62	61	61	59	58	58	58	56	56	56
Low	46	46	47	47	47	48	50	48	48	48
	2043	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**		
High	79	78	78	79	79	79	81	82		
Central	56	56	56	56	56	56	56	57		
Low	48	48	48	49	50	51	52	54		

Be aware that these values, are the raw capture price data. For the real option analysis these values had to be adjusted to the correct floor and ceiling of the specific subsidy regime.

5.2 Real Options Analysis

To incorporate the expected fluctuations of the electricity prices in the time horizon of the coming five years as well as valuing the option to repower the existing plant, it is proposed to make use of a binominal tree model, which aims to simulate stochastic processes. The basic concept of a binominal tree model is that it incorporates volatilities in the underlying cashflow and applies this volatility to discrete time steps, in this case yearly. For each time step there is the possibility of two outcomes, thus the name binominal. The following Figure 18 represents a typical recombining binominal lattice tree. "Recombining" referring to the fact that two bifurcations meet at the same node, avoiding an exponential growth of nodes, and thus much higher computational effort (Mun 2002, 141–42).

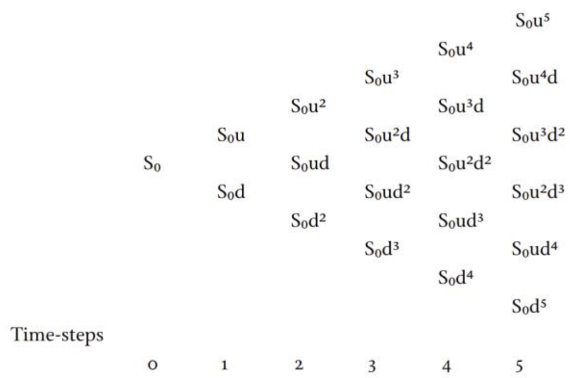


Figure 18: Example of Binomial Tree

More complex models might include trinomial or multinominal lattice trees (see the pentanomial example of Ritzenhofen & Spinler in the literature review). For this model a binominal model was used, which thus results in either an up- or down-scenario. However, since not the whole time-horizon of the model is analyzed, the input data for the volatility calculation was reduced to the coming five years, resulting in a volatility spread (due to the Monte Carlo Simulation) between 0.37 and 0.39.

To calculate the up and down factors for each node, the following two formulas are used, where e is set at 2.718, the volatility σ calculated by the Monte Carlo Simulations ranges from 0.37 to 0.39 and will be incorporated dynamically into the model. Meaning that no fixed value is estimated, but instead the model recalculates the volatility for every observation. T describes the time between the period nodes, which in this case is one year, thus T = 1.

$$u = e^{\sigma\sqrt{T}}$$

$$d = \frac{1}{u}$$

The Monte Carlo Simulation down movement (*d*) factors range from roughly 0.67 to 0.69. For the up movement (*u*) values between 1.43 and 1.49 can be expected. Again, these values fluctuate between the given figures, as their calculation is based upon formulas (see formulas above) which include the dynamically calculated volatility of σ (see section 4.2). Additionally, it is vital to understand that these values represent the multiplication factors by which the underlying DCF value is multiplied by. They do not represent the probabilities at which these factors will be applied. For this the following formula is used in the option value tree and represents a risk neutral probability.

$$\mathrm{p} = \frac{e^{(r_f \delta t)} - \mathrm{d}}{\mathrm{u} - \mathrm{d}}$$

Thus, p is the probability that an up movement (u) occurs, whereas 1-p represents the opposite down movement (d). Additionally, a risk-free rate (r_f), which represents possible returns on a quasi-risk-free asset such as ten-year German treasury bonds at a return of around 3% per annum, is defined. Lastly, δt describes the timespan between each interval.

5.2.1 Option A: Existing Wind Farm

According to Figure 18 the binominal tree of the underlying asset - the not-repowered plant continuing production until the expected end of lifetime - is built. For concept visualization, the tree-layout as seen in Figure 18 provides itself. However, creating the tree in EXCEL, removes the spatial cohesion of a calculative up movement, resulting in a visually higher cell, but rather, due to the nature of the program the model has a triangular-wedge form, as seen in the following table, which represent the binominal tree for one exemplary run of the underlying asset value.

Table 8: Binomial Tree of the Existing Wind farm

	Year 1	Year 2	Year 3	Year 4	Year 5
57.672.057 €	83.818.671 €	121.819.301 €	177.048.167 €	257.315.984 €	373.974.591 €
	39.681.686 €	57.672.057 €	83.818.671 €	121.819.301 €	177.048.167 €
		27.303.277 €	39.681.686 €	57.672.057 €	83.818.671 €
			18.786.222 €	27.303.277 €	39.681.686 €
				12.925.999 €	18.786.222 €
					8.893.829 €

We clearly see that even under uncertainty, the value of the asset over the coming five year remains positive. Interestingly, the high volatility is attainable through Table 8, as the total value spread in year five is between plus and minus 650% of the non-dynamically calculated value. Nevertheless, the farm remains stably in the money.

5.2.2 Option B: Repowered Wind Farm

Having defined the business case with which the option to repower with is compared to, it is now necessary to perform the calculation of the option to repower binominal lattice tree. This is done using the principle of backward induction, which the reader might recall from the introduction of this thesis. First the last nodes of the option to repower tree need to be defined. This is done creating a second binominal tree model which assumes a wind farm that has been repowered with the key input factors that were shown in Table 2. This results in the following present value calculation:

Table 9: Present Value Calculation of the Repowered Wind farm

	Year 1	Year 2	Year 3	Year 4	Year 5
Discounted Costs	-5.109.085 €	-4.735.193 €	-4.388.663 €	-4.067.493 €	-3.769.826 €
Revenues	37.594.964 €	24.328.950 €	21.492.774 €	20.653.228 €	20.653.228 €
O&M	-5.619.994 €	-5.729.584 €	-5.841.311 €	-5.955.216 €	-6.071.343 €
Nominal Cashflow	31.974.971 €	18.599.366 €	15.651.464 €	14.698.012 €	14.581.885 €
Discounted Cashflow	29.068.155 €	15.371.377 €	11.759.176 €	10.038.940 €	9.054.204 €

Following the calculation of the present value of the repowered plant, which resulted in a figure of 95.505.698 € (again the sum of the nominal cashflows in Table 9, see section 4.5), the binominal tree just like in the previous section, is built. The vital parameter of the electricity price has to be adjusted as well, as discussed towards the end of section 5.2.1, as the subsidy schemes the two plants operate under, differ in their floor price. Applying the binominal model to the repowered plant gives us the following binominal lattice:

Table 10: Binomial Tree of the Repowered Wind farm

	Year 1	Year 2	Year 3	Year 4	Year 5
95.505.698 €	140.757.477 €	207.450.107 €	305.742.527 €	450.607.111 €	664.110.321 €
	64.801.804 €	95.505.698 €	140.757.477 €	207.450.107 €	305.742.527 €
		43.968.830 €	64.801.804 €	95.505.698 €	140.757.477 €
			29.833.398 €	43.968.830 €	64.801.804 €
				20.242.331 €	29.833.398 €
					13.734.673 €

The repowered value tree shows that an approximate 140% increase in revenue can be expected. Assuming that the plant continues to operate under the current subsidy regime, the detail repowering value calculation results, are shown in in Table 10 above. It follows intuition that the larger repowered plant does indeed generate more revenue, throughout all scenarios. However, this value comes at the cost of expansion, which is the sum of the lost revenues during construction and the upfront costs of the new turbines.

5.2.3 Option Value

In the next step the two lattices have to be combined to receive the necessary information on the actual value of the option to repower, using the aforementioned method of backwards induction. Initially, the final nodes of both trees are assessed, by identifying which node has the greater value. It must not be forgotten to incorporate the exercise cost of calling the option to repower. The exercise price are the investment costs (CAPEX) in addition to the lost revenues of one whole year of operation of the existing plant due to the necessary construction works when repowering the plant. A linear trend in expansion costs is assumed, as the costs are mainly driven by the cost of the turbines. However, it is assumed that the technological development negates inflation and consequently the increase in turbine costs. Including the cost of exercising the option is easily achievable in EXCEL using the following formulaic logic:

=MAX([final node of repowering]-[exercise price];[final node of non-repowered plant])

For the intermediate notes it is necessary to perform a more complex calculation, as these nodes are the ones which actually include the backwards induction methodology using a risk neutral probability *p*. The basic formula looks as follows, where “up” is defined as the next up-node in the tree and “down” vice versa:

Table 11: Intermediate Node Calculation

	up
base	
	down

Thus, in the “base” cell, the backwards induction is calculated as:

$$[(p)up + (1 - p)down]\exp[(-riskfree)(\delta t)]$$

Finally, this has to be combined again with a maximization logic to find the financially most favorable variant, resulting in:

=MAX([corresponding node of non-repowered plant; corresponding node of repowered plant] – [exercise price];$(((p)up + (1 - p)down]\exp[(-riskfree)(\delta t)$)

Continuing this formula for every intermediate, as well as the initial node, the option value was successfully identified via creating the option value tree. In the case of the plants at hand, the following results are gathered (again be aware of the fluctuations due to the dynamic Monte Carlo Simulation base). As previously outlined a maximization between letting the wind farm continue in a non-repowered vs. repowered state is performed, resulting in the following numeric table:

Table 12: Repowering Option Value Tree

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
61.427.955 €	87.887.319 €	125.743.742 €	179.906.371 €	257.398.911 €	368.270.446 €
	41.864.475 €	59.897.102 €	85.697.070 €	122.610.068 €	175.422.904 €
		28.531.542 €	40.821.166 €	58.404.400 €	83.561.404 €
			19.444.860 €	27.820.504 €	39.803.857 €
				13.252.091 €	18.960.273 €
					9.031.586 €

Table 12, depicts the to be expected cashflows under uncertainty, with the maximization approach outlined in the previous paragraphs. Meaning, that the most lucrative option, be it to continue operation of the existing plant or to decide to repower it, is chosen. Thus, this table shows the value of the non-repowered wind farm including the optional value of possibly repowering the whole wind farm in the next five years. However, just from the raw figures it is not possible to easily identify which amount correlates to which decision. For this see Table 13 in Section 5.3. where the figures are represented with the corresponding management decision.

To sum up, the financial performance under electricity price uncertainty of the underlying, non-repowered plant was assessed by applying a binominal tree model to the present(non-discounted)-value of the plant. Then, similarly the repowered plant was modelled and binomially assessed. By using a maximizing function and backwards induction, the value of the option to repower the plant was assessed. Now, in the following section the results are reiterated and interpreted

5.3 Comparison and Lessons Learnt

If each maximization is now correlated with the corresponding management decision recommendation, a table is generated, which displays the achieved results in a more easily graspable manner:

Table 13: To Wait or to Repower?

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
REPOWER	REPOWER	REPOWER	REPOWER	REPOWER	REPOWER
	REPOWER	REPOWER	REPOWER	REPOWER	WAIT
		REPOWER	REPOWER	REPOWER	WAIT
			REPOWER	REPOWER	WAIT
				REPOWER	WAIT
					WAIT

Showing that in most cases the option evaluation recommends to repower the existing wind farm before its expected end of life time. The increase in suggestion for the option to wait in year five can be explained by the drop in electricity prices (see Table 7), due to the fact that an early repowering of the plant enables the newer, more powerful turbines to benefit from the high electricity prices. Additionally, it might be of advantage to be aware of the actual value of the option to repower. This can prove itself useful if, for example, the asset owner wants to sell the wind farm and aims to adequately capture the value of the option to repower the plant which comes with selling an existing wind farm which nears its expected end of turbine lifetime. The discrete option value is shown in Table 14:

Table 14: Actual Numeric Value of Holding the Option

	Year 1	Year 2	Year 3	Year 4	Year 5
4.547.528 €	6.967.591 €	11.656.784 €	21.444.295 €	42.857.575 €	90.911.357 €
-	1.644.561 €	1.788.647 €	1.729.222 €	1.253.839 €	-
-	-	841.880 €	813.909 €	590.156 €	-
-	-	-	383.090 €	277.774 €	-
-	-	-	-	130.743 €	-
-	-	-	-	-	-

In conclusion, even under electricity price uncertainty and including a drastic increase in turbine costs, the financial benefits of repowering the existing wind farm have been numerically proven. The ROA has shown that the value of holding the option and not executing it until uncertainty has been resolved does not outweigh the increase in revenue when deciding to repower the wind farm. Thus, the managerial decision which should be taken according to the calculation of this paper is to repower the existing wind farm. An added benefit of the real option analysis undertaken in this paper is that the current value of holding the option and not repowering the plant has been defined. Thus, if a sale of the not repowered wind farm is sought after, the management staff now has the ability to incorporate this value into the sales process.

6 Conclusion

To sum up, this thesis explored the topic of optional value in real assets in a repowering context of a wind farm situated in Austria, trying to answer the question whether or not the option to repower an asset, has intrinsic value. The thesis explored the background of electricity production via the power of wind, showing that the historic wind power plant installation pattern is heavily dependent on the composition, and timing of subsidy schemes. This correlation was presented using the Austrian renewable energy sector as an example. Most notably, Section 2.2 revealed that the introduction of legislative packages revolving around the issue of financial subsidy schemes, results in an increase in wind power plant installations. This, in combination, with a rather static turbine lifetime, spanning state of the art turbines from reputable manufacturers, results in an accumulation of repowering scenarios across the whole sector. In addition, the increase in turbine capacity and efficiency, spans the entire market, and positively effects the interest of wind farm owners and operators to repower their existing assets.

Setting the scene by presenting the most common financial forecasting model, the Net Present Value analysis, the thesis continued by presenting the methodology of real option evaluation. Arguing, that an asset like a wind farm, has additional value besides the sum of the discounted future cashflows. Focusing on the fact that the managerial flexibility of the asset holders has to be incorporated in estimating the financial viability of a wind farm. In the case of wind power plants, a key aspect of managerial flexibility is the option to repower an existing plant. From a methodological, argumentative perspective the example of a wind farm owner deciding to repower a wind farm was presented. Showing that in many cases, decision makers valued their wind farm using historic revenue patterns and extrapolating them into the future (NPV Analysis), however, if you assume that the plant will be repowered, these historic extrapolations do not adequately represent the future revenue of the asset at hand. Thus, exploiting the powerful Real Option methodology emancipates decision makers by enabling them to embrace the actual value of their assets. This was proven by calculating the option value of repowering an existing wind park asset in Austria, resulting in a notable increase in asset value, confirming the applicability of the methodology.

The model relied heavily on real world data which was audited for the repowering context. By applying correction factors to the existing wind speed data, it was possible to create a wind speed distribution at the height of the turbines which would be used in a repowering scenario. This data was then cross referenced with the power curve of an exemplary state of the art turbine. Ultimately, this resulted in the creation of a load distribution estimation of new turbines from which the expected production was estimated. Additionally, the issue of technical degradation was analyzed with the ultimate conclusion that in the case of the actual wind farm at hand the technical availability may be included in the model, using industry standard technical degradation estimations, as the technical availability did not show anomalies which would have made it necessary to focus more heavily on this factor.

Concerning, the volatile nature of the current electricity market in Europe, the model incorporated this aspect as its main risk-factor. By calculating the volatility of the electricity prices over the option horizon, it was possible to create a sound market electricity price market scenario. Furthermore, due the large spread between the low and high electricity price scenarios, a comprehensive Monte Carlo Simulation was applied. This method was presented as it can be applied in environment which resembles the computational realities and abilities of most renewable energy companies in the sector.

For future research, the binomial real option approach presented in this thesis can certainly be expended on. This might be achieved by making use of direct programming approaches, which due to their increasingly, laborious computational effort, present a compelling option to build upon the binomial approach. Even though, the real option approach has proven itself to be a reliable method, the Net Present Value prevails in the world of financial analysis. A key factor in the strong presence of the NPV approach is that financial institutions, rely on NPV calculations for the process of granting credit and upfront investment. Meaning that, even if corporate decision makers include the real option methodology in their everyday processes, the NPV calculation will continue to be an essential part in financial modelling, as financial institutions and banks require credit applicants to present a viable business opportunity using the future discounted cashflow of the asset.

7 Abbreviations & Acronyms

CAPEX	Capital Expenditures
COVID-19	Coronavirus SARS-CoV-2
DCF	Discounted Cashflow
EU27	27 Member States of the European Union
GBM	General Brownian Motion
IPCC	International Panel on Climate Change
MCS	Monte Carlo Simulation
NPV	Net Present Value
OPEX	Operational Expenditures
O&M	Operation and Maintenance
ÖSG	Ökostromgesetz
PPA	Power Purchase Agreement
PV	Present Value or Photovoltaics
ROA	Real Option Analysis
SCADA	Supervisory Control and Data Acquisition
UN	United Nations
WACC	Weighted Average Cost of Capital
WTG	Wind Turbine Generators

8 List of Tables

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10 Bibliography

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