Using economic indicators in a simple model to predict annual growth in the wind energy industry

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended on September 14th 2022.

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Project duration:	February, 2022 – September, 2022
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Abstract

Climate change is going to be the main problem this and future generations will face. Wind energy is promising to be one of the industries that could help mitigate this impending crisis. In literature many different models and predictions can be found to describe the possible futures of wind energy. But there is still a lot of uncertainty in this field as to what factors play which role in its development. This research contributes to this challenge by comparing the economic attractiveness of windmills expressed as Net Present Value(NPV) with annual added wind capacity in five countries for 2008 till 2019. The countries used for this research are Germany, Denmark, Canada, Texas and Sweden. This research found an exponential relationship between the NPV and added wind power capacity. A 10% increase in NPV(€/MWh) found an increase of 15% for the annual added wind capacity(MW/TWh) of added windmill capacity per TWh of electricity produced. The vast amount of data sources used could have lead to a higher uncertainty regarding their uniformity and trustworthiness. Doing a sensitivity analysis yielded no improvements in the results. The simple economic model used was able to describe the growth in wind energy in countries, though there is still a significant spread in the results. A likely explanation for this spread is the lack of several important aspects such as permits, company influences, cultural differences and social-economic challenges which were all not taken into account. This research also makes several recommendations regarding possible policies countries could in order for them to reach their wind or clean energy goals.

Acknowledgements

I would like to thank my supervisors, Kornelis Blok and Enno Schröder for their help and support during the past six months. The regular meetings and critical questions of Kornelis kept me on the right track and his enthousiasm about climate change science inspired me to dive into this field. Simone, Willemijn and Maartje have been very helpful in keeping me motivated during collective study sessions. Laurens, Jochem, Tim and Tom I would like to thank for being awesome roommates who were willing to ride along on the rollercoaster called afstuderen. My parents, Marie-France and Redmer(senior) I want to give special thanks for their everlasting help and guidance during these trying times, my student life and everything that came before. Bas and Marije have not been closely involved in this project but very much so in my life, for which I am very grateful. Finally I want thank Nerine, for everything.

Contents

Chapter 1

Introduction

1.1 On the role of wind power in climate mitigation

The consequences of climate change are going to form the major challenges to face future generations. Mitigating the emission of greenhouse gases will be and already is one of the major goals of our society, as every tenth of a degree of climate warming that can be saved will prevent many major catastrophes. Mitigating and eventually stopping the production of greenhouse gases means a drastic and fast change in the way society is shaped. The energy sector will have to switch over to sustainable forms of energy production, the average global energy use will have to decrease and many resources like land, metals and animals will have to be treated in a whole different manner. How this will be done nobody knows for sure yet, but it is certain that it needs to happen.

On the other hand, the earth has already warmed 1.2 degrees Celcius since the 19th century and is very likely to go over 1.5 degrees Celcius[Masson-Delmotte et al., 2021]. This warming of the earth has set irreversible processes in motion which we will have to deal with in the next decades, centuries and millennia. Sea levels will rise, vast land areas will become uninhabitable, many millions of species will go extinct and mass surges of climate refugees will crash on the still inhabitable lands.

To understand what can and needs to be done on both the fronts of climate mitigation and adaptation research will continually be needed. One of the big open questions is what the sustainable energy technologies of the future will be. Solar and wind energy will definitely play a role, but how big a role, in what places and for what industries still remains to be seen. Gaining a better understanding of the possible progress of these technologies could help policymakers to choose what technologies to subsidize and what rules to make to help shift mankind towards a sustainable era.

This research will look at the empirical relationship between the amount of wind energy capacity built in a country per year and the Net Present Value(NPV) of wind energy. To research this the principle by [Williams et al., 2020] is used. In this paper, the relationship between the NPV of solar panels and the added solar power generation per capita was researched for the past 10 years and fitted to an error function.

The main research question of this paper is:

"What is the relation between the economic attractiveness of building wind energy and added wind capacity in a year?"

This research addresses one of the grand challenges of this generation. Creating a world fit for climate mitigation and adaptation. Creating a model which can give insight into the possible scenarios surrounding sustainable energy technologies can give policymakers tools upon which to base their decisions. Many current policies are failing to prepare humanity for the coming generations. There is no set of solutions to tackle all problems at once or equally. This research combines modelling with policy advice to pave the way for policymakers to make policies for a better future.

In this chapter, Introduction, the literature and reasoning for doing this research is layed out. How the main research question is tackled is described in the chapter 2, Method. Since data gathering was a major part of this research chapter 3, Process is dedicated the the gathering and quality of the data. All findings can be found in chapter 4, Results. These find are subsequently discussed in chapter 5, Discussion and this research and its findings are concluded in chapter 6, Conclusion.

1.2 Literature review

1.2.1 The role of wind power in climate mitigation

Global expansion in the use of wind energy can play a major role in delaying or even avoiding crossing the 2°C global warming threshold[Barthelmie and Pryor, 2014]. From 3.5% of the global energy supply in 2015 wind power will have to account for around 36-37% in 2050[Gielen et al., 2019][Jacobson et al., 2017]. This means an increase of about 6.8% per year is necessary for the coming 35 years. Sustainable electricity generation can be implemented on large scale. An example is Blakers et al. [2017], which showed that solar and wind power could provide 90% of the electricity demand in Australia. And although the installed wind energy capacity has grown over 20% annually since 2000[Pryor et al., 2020], a lot more needs to be built for the world to keep global warming at a minimum. Best and Burke [2018] found out that making use of carbon pricing increases the use of solar and wind energy. Due to the rising temperatures, the climate we live in will not only become warmer, but also more extreme[Masson-Delmotte et al., 2021]. This increase will also lead to more wind, which could lead to more potential for wind power generation. Europe, especially the northern regions may see a significant increase in their average wind speeds resulting in more wind power generated[Hosking et al., 2018]. Concluding, wind energy will play a major role in the oncoming battle of climate mitigation.

1.2.2 Energy transitions

A lot of research has been done on the development of new technologies. And with recent years also on the energy technologies. Research shows that formative phases of energy technologies last about 22 years on average[Bento and Wilson, 2016]. Although estimations go from 20 to 70 years[Gross et al., 2018]. With technologies that can replace existing technologies being on the shorter end of the spectrum. There is agreement on the fact that, though new technologies should not be overlooked, the major focus of policy makers should lie on deploying currently existing energy technologies.

The introduction of new technologies is often described as laying on an S-curve. With the technology needing some time to take to the markets, an inflection point and saturation at the end of its life cycle as can be seen in figure 1.1. These S-curves are often quite successful in describing the deployment of a technology. Though theoretically interesting they are not well suited for predicting what the final market penetration or future growth rates will be[Cherp et al., 2021].

1.2.3 The wind energy industry

How the wind energy industry is relatively new and vastly growing in many countries. And each country has its own approach to setting up this industry. In the Netherlands the government researches potential sites for offshore

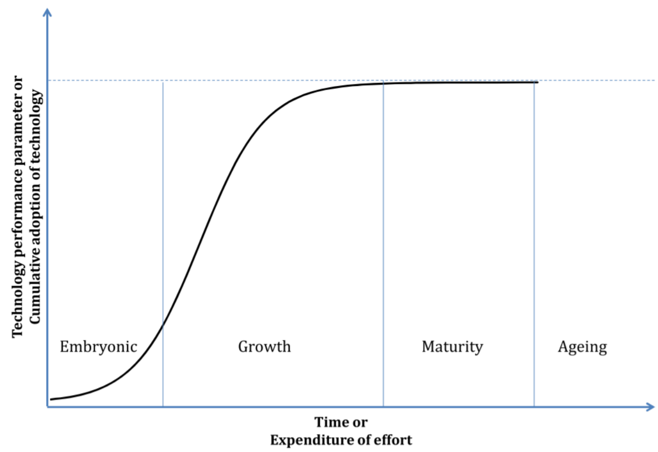


Figure 1.1: Often used technology S-curve[Taylor and Taylor, 2012].

wind energy, before offering them up by means of competitive tendering. In this process wind farm developers can bid for permits[NLg, 2019]. Small scale enterprises play a substantial role in the building of onshore wind farms. This can be largely attributed to the maturity, modularity, high reliability, the simplicity of the power generation process, and availability of technical service providers for these technologies[Yildiz, 2014]. The size and frequency of these wind farms can be heavily influenced by the amount of government help and its form. Subsidies and soft loans being highly effective[Curtin et al., 2018]. One of the biggest shortfalls for these small scale businesses is a l ofack financing, particularly private financing[McInerney and Johannsdottir, 2016].

1.2.4 Growth of the wind energy industry

Global wind energy has seen a major growth over the past decades. From 17.4GW in 2000 to 486GW in 2016 the industry has, and still is growing at unprecedented rates. This industry was mostly taking place in the US, China, India and western Europe ten years ago. Nowadays half of all countries worldwide have invested in some form of wind energy [GWEC, 2017]. The total wind industry currently also employs over 1 million workers [Raturi, 2019]. This industry increase can at least partly be explained by a drop in costs for wind energy. The latest IPCC report found that for both onshore and offshore wind the unit costs of energy have dropped since 2010 while adoption increased significantly[Shukla, 2022]. Though the wind industry will grow over the coming years, there are many uncertainties when it comes to predicting the future amount of wind energy. There are many different models which all make use of different methods and input variables that all give a very wide range of possible future scenarios[Qian et al., 2019]. It is also interesting to note that the wind energy market seems to be largely dominated by a select number of large companies, especially in the offshore wind industry. In 2013 Siemens Wind Power and Vestas together were responsible for 83% of all installed offshore wind farms[Sovacool and Enevoldsen, 2015].

Many different studies are being done on the effects of policies in the wind industry. Often, these studies show how little understanding there is of these effects[Kelsey and Meckling, 2018]. In the race towards renewable energy there is now increasing proposition to not only opt for changes in wind energy policies. Geels et al. [2017] suggests that a complete sociotechnical framework rework is necessary to successfully accommodate for a rapid change to wind energy. Despite the vast amount of literature written on policy effects and modelling for the future of wind energy there are still many uncertainties into how economic factors influence the development of the wind industry[Jefferson, 2014]. This research tries to attribute to this challenge by providing a simple model to predict the growth of the wind industry in a country using economic parameters.

1.2.5 Combining NPV with produced energy for wind sector in current literature

Combining net present value(NPV) with the amount of solar power generated is done by Williams et al. [2020], the result of which can be seen in figure 1.2. This paper and its results were the main inspiration for the topic of this research. Other papers like Beuse et al. [2020] and Tibebu et al. [2021] make use of this method by applying it to specific regions like South-East Asia and the US. This is a trend seen in more research on solar energy, which often focuses on one geographical area[Solaun and Cerdá, 2019]. And although there have been studies on the effect of carbon pricing and policy support on the use of wind energy[Best and Burke, 2018]. A simple model like the one by Williams et al. [2020] has not been applied for wind energy.

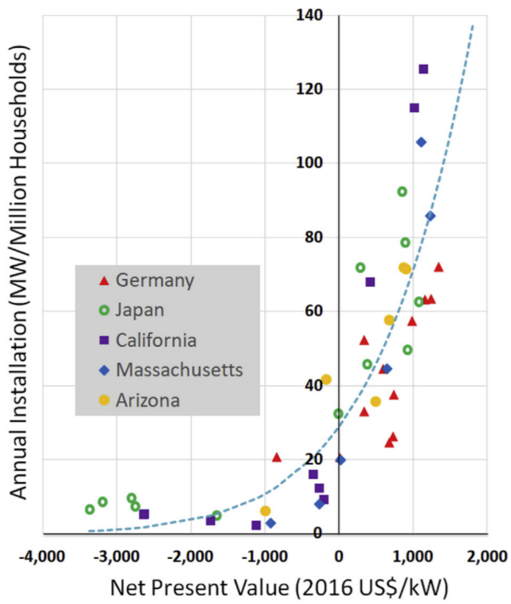


Figure 1.2: "Annual residential PV installations versus Net Present Value for homeowners in five regions. Each data point reflects an annual figure for the region from 2005 to 2016. The dotted line is the fit from the error function model"[Williams et al., 2020]

1.2.6 Calculating the NPV of installed wind energy

Research on the economic viability of building windmills differs greatly in range. A study about the NPV for building a windmill for farmers in Germany found an NPV of about €383,000/MW[Fuchs et al., 2019]. A study about building a potential wind park in Algeria found an NPV of $2.3Million/MW[Himri et al., 2020]. These differences can be attributed to differences in production costs, subsidies, energy tariffs and average wind speeds in different countries. There are many different measures for measuring the economic performance of renewable energy. An example being the levelized cost of energy(LCOE). LCOE is defined as the total costs of an electricity generator over its entire lifetime divided by the total power output over its lifetime. This type of metric is more often used in comparing different technologies. NPV is used in this research because it is very intuitive to understand. The NPV also covers a larger part of the project as the benefits, which are subsidies and revenue from electricity are also taken into account.

Chapter 2

Method

To answer the research question a model similar to that described by Williams et al. [2020] will be made for wind energy. For multiple countries over multiple years the economic viability, expressed in Net Present Value(NPV), will be compared to the annual wind electricity capacity installed. The Net Present value will be measured from the perspective of the contractor of the windmill, which is the actor that funds the project and receives the rewards from it. The hypothesis is that the relationship between the NPV and annual added wind electricity capacity can be described using the error function. The reason for this hypothesis lies for a large part in its simplicity. There are many ways to describe the relationship between two factors, the error function(the primitive of the normal distribution) being one of the more elegant as will be explained in section 2.2.

2.1 Net present value

One of the two main variables used in this model is Net Present Value(NPV) as experienced by the contractor of the windmill. This contractor is defined as the party that pays for building the windmill and receives money for the electricity it provides and any subsidies that apply. The NPV encompasses many other variables like subsidies, capital costs and lifetime of the windmill into one variable. Another variable that is often chosen in this type of economic studies is the Levelized cost of electricity(LCOE). An LCOE calculates the total costs that are made per unit of electricity. Though this can be an insightful variable, it only looks at the investments made. The benefits, like subsidies and revenue from the sale of electricity, are not taken into account. For the contractor, these can be important aspects as they determine whether or not, and how much, commissioning the building of wind energy will be beneficial. Therefore NPV was chosen since it gives a more complete picture of the choices a contractor has to make. There are some degrees of freedom when it comes to calculating an NPV. This mostly comes down to simplification of the formula. A self-defined version of the NPV, based on Williams et al. [2020], allows for a workable model within the given time frame and collectible data. For a proper comparison between different windmills, this NPV is defined in euro per Mega-Watt hour of wind energy.

NPV($€/MWh$) for wind energy is defined as:

$$NPV_y[€/MWh] = -C_y + \sum_{i=0}^{N} \frac{[EP_y \cdot (1+inf)^i + S_{y+i} - OM_{y+i} - D_N}{(1+disc_y)^i}, \qquad (2.1)$$

- y denotes the year the NPV is calculated for,
- C_y the total capital costs of building the windmill in year y(€/MWh),
- N the expected lifetime of the average windmill(years),
- EP_{y+i} the electricity price in year y(€/MWh),
- inf the expected yearly increase of the electricity price expressed as the annual average inflation of that country(%),
- S_{y+i} the subsidies received per MWh of wind energy produced in year y+i(€/MWh),
- OM_{y+i} the nominal operation and maintenance costs of the windmill in year y+i(€/MWh),
- D_N the decommissioning costs of the windmill in year N (€/MWh),
- $disc_y$ the discount rate in year y.

This formula is best understood when divided up into two categories. First of all there are the one-time costs, capital and decommissioning costs, of which the last one is only paid at the end of the windmill's lifetime. In the other category fall all costs and benefits that vary throughout the windmill's lifetime, N. These include the electricity price, subsidies and operation & maintenance costs. The latter two are simply received or paid each year. The electricity price is prone to change, which necessitates the term for the yearly expected increase in electricity price. The discount rate is taken to be equal to the interest of the country in that year.

2.1.1 Currency changes, inflation and discount rate

Since inflation and exchange rates can greatly influence prices of electricity, O&M costs, and subsidies throughout the years, and since this model compares countries with different currencies some monetary adjustments have to be made. First the NPV is calculated in the currency of the country studied with the nominal prices of that year[World-Bank, 2020]. The local currency is then exchanged to Euros using the average exchange rate of that year. Next, these nominal prices are converted to real 2020 Euros. This conversion could also have been done the other way around. The reason this order was chosen is that price indexes can differ greatly for different countries. This could result in numbers from 20 years ago looking very skewed compared to other countries if that countries has had a major shift in their price indices. For the discount rate the average annual lending interest rate per country is taken corresponding to the year the NPV is calculated[IMF, 2022].

2.1.2 Lifetime of windmills

Around the year 2000 windmills were said to last about 15 to 25 years[Krohn, 1997][Gurzenich and Mathur, 1998]. The lifetime of windmills today is generally estimated around 20-25 years[Luengo and Kolios, 2015][Sawant et al., 2021]. One possible explanation of the increased estimated lifetime of windmills is found in material discoveries which help to extend the lifetime of windmills [Vestas, 2005]. The lifetime of a windmill can be influenced by factors like geography and maintenance. Since this model only looks at the average expected lifetime of windmills regional differences will not be looked at. To estimate the increase in lifetime expectancy over the years, a linear regression will be made using a lifetime of 20 years in 2000 and 22.5 years in 2020. This means there is an expected lifetime increase of 0.125 years every year.

2.1.3 Operation & Maintenance costs

Around 2003 lifetime average operation and maintenance(O&M) costs for windmills were estimated around 12-15 €/MWh produced[Iuga, 2003] in Denmark. O&M costs in Denmark ranged from €40/kW/yr in 2008 to 33 €/kW/yr in 2016[Noonan et al., 2018]. Currently estimates are around 20-25% of the LCOE [Costa et al., 2021]. Wiser et al. [2019] of Lawrence Berkeley found that projects built in the US in the 1990s cost about $23/MWh to $11/MWh for projects built in 2018. Linear regressions between the found data will be made to make an educated guess over the whole period.

2.1.4 Electricity prices

Electricity prices for consumers are influenced by many factors outside of energy generation. Examples are transmission and distribution costs, taxes and supply & demand.The consumer prices therefore do not directly reflect what the builder of a windmill receives for delivering the energy. This problem is tackled by making an educated estimation of the fraction of the electricity price that is received by the electricity generating party. For each country and for every year, the industrial electricity price without taxes is taken as a basis and multiplied with this factor. The factor is taken at 55%[EIA, 2021][BDEW, 2022]. The electricity price in Germany will be treated differently since this country works with a fit price, therefore electricity price will be taken together with subsidies as a single revenue in the subsidies.

2.1.5 Time lag

This model looks at the relation between the NPV of wind energy and the annual added wind electricity capacity. What must be noted here is that there is a delay between the decision to install wind energy and the actual date of commissioning. This will be referred to as the time lag. In literature an average time lag of 8 to 10 years has been found for offshore[RVO, 2022] and 4 to 5 years for onshore[Cena, 2010]. To calculate the NPV for a given year the average time lag of every country is calculated. Denmark has about 20% of its wind electricity capacity offshore. Texas and Canada have near to zero offshore wind parks. Sweden has about 3% offshore wind electricity capacity. Germany has 14% offshore wind electricity capacity[IEA, 2017]. To reduce outliers in this model a spread will be applied to the final results in which 25% of the data will be taken from year $y - \Delta y - 1$, 50% of the data will be taken from year $y - \Delta y$ and 25% will be taken from year $y - \Delta y + 1$. In which Δy denotes the difference in years between the decision to build the windmill and the delivery of the windmill.

To write this down more formally

$$\Delta y = \%offshore * 9years + \%onshore * 4.5years, \tag{2.2}$$

$$NPV_y^1 = \frac{1}{4}NPV_{y-\Delta y-1} + \frac{1}{2}NPV_{y-\Delta y} + \frac{1}{4}NPV_{y-\Delta y+1}, \tag{2.3}$$

in which $\%offshore$ and $\%onshore$ are the percentages of windmills which are respectively offshore or onshore. y is the year the NPV is calculated for and Δy is the time lag for windmills as described above.

2.1.6 Decommissioning costs

After the lifetime of a windmill has expired it will most likely need to be removed, upgraded or replaced. There are costs that come with this and different countries have different ways of dealing with this problem. In Texas, rules on decommissioning and decommissioning funds have only been established in 2019 [Pence, 2019]. Before this, windmill builders had no requirements on setting money aside for decommisioning. The UBA gives €$30,000 - 60,000/MW$ as estimated costs for dismantling[Knight, 2021] onshore windfarms. An average of €$45,000/MW$ will be used in this research. In the model used for this research, decommissioning costs will only attribute about 0.5% of the NPV.

2.2 Annual added wind

Often in literature, the amount of wind electricity a country produces is defined as the wind electricity capacity in megawatts or gigawatts, either in total, per capita or per household. Though these can be insightful numbers, the problem is that they make it hard to actually compare countries. China, for example, is very much in the lead when it comes to the total wind electricity produced with 328 GW in 2021 [Xu and Stanway, 2021]. But when looking at electricity produced per capita, or at wind electricity as a fraction of total electricity produced they score much worse compared to other countries. Furthermore, this model specifically looks at wind and total electricity generated over wind and total energy generated. An important consideration in this choice is the availability of data on these numbers. There is also not one clear definition in what to include in total energy generated by a country. For this model the NPV will be compared to the Annual added wind electricity capacity which is defined as:

$$\text{Annual added wind capacity} = \frac{\text{Annual wind electricity capacity(MW)}}{\text{total electricity generated(TWh)}} \tag{2.4}$$

Since wind energy project are mostly of considerable size the delivery of a single wind park can influence the annual added wind capacity a lot for a given year. Because of these yearly variations a spread will be applied in which 25% of the data will be taken from year y-1, 50% of the data will be taken from year y and 25% will be taken from year y+1. The formula for Annual added wind(AAW) than becomes down as

$$AAW_y^1 = \frac{1}{4}AAW_{y-1} + \frac{1}{2}AAW_y + \frac{1}{4}AAW_{y+1}, \tag{2.5}$$

in which y is the year the windmill was placed.

At the foundation of this model there is one key assumption. The increase in the annual added wind electricity capacity as function of NPV can be described as a normal distribution as shown in figure 2.1. This assumption is based on the technology S-curve [Taylor and Taylor, 2012]. As the NPV for windmills in a country increases there will be more and more companies that will decide to built a windmill. For low NPV the increase in the wind electricity capacity is very slim. At some point there will be a peak in increases, μ in the formula below. After this peak an increased NPV will have a smaller effect on the annual added wind electricity capacity since most of the companies that would buy a windmill for this NPV have already decided to do so for a lower NPV. In other words, an increased NPV will still lead to an increase in windmills being build but at a smaller rate.

To compare the NPV with the actual wind electricity capacity, the scaled cdf of the normal distribution, the error-function(inspired by Williams et al. [2020]), is taken as

$$\text{Annual added wind capacity(NPV)} = \alpha \int_{-\infty}^{NPV} e^{-\left(\frac{x-\mu}{\sigma}\right)^2} dx = K\left(1 + \text{erf}\left(\frac{NPV - \mu}{\sigma}\right)\right), \tag{2.6}$$

where erf(x) is the error-function, the integral of the normal distribution. α is an arbitrary constant and K is the integration constant which represents half of the maximum wind electricity capacity or final market penetration. K will be

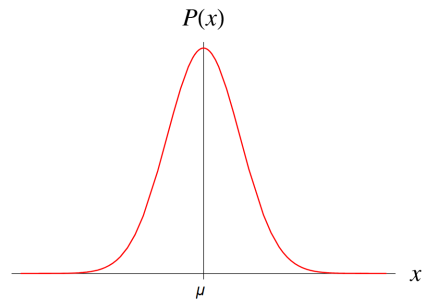


Figure 2.1: Standard normal distribution[Ahsanullah et al., 2014]

fixed at 50% of the total produced electricity in that year.μ is the NPV which has the highest change in adoption. σ is the spread around μ. Both of these values have to be determined empirically.

As mentioned before, the central assumption behind this model is that companies investing in wind energy will decide about building wind parks with regards to the NPV. What the relation is between NPV and the building of new wind farms takes shape can be found in μ and σ. This represents the NPV for which change in wind electricity capacity is at its peak and the spread around this peak.

2.3 The model

In the previous section the NPV and annual added wind capacity have been described. This section will describe the methods used to test the hypothesis of this research. Using data about the five regions, as explained in chapter 3, a plot can be made with the NPV(€/MWh) on the x-axis and the annual added wind capacity on the y-axis. To test the research question, an exponential function will be fitted to the data using least squares(LS) and ordinary least squares regression(OLS). The exponential function is used as an estimator of the error function. The reason for this choice is that the error function is too difficult to properly fit in this research. The exponential function was chosen because it resembles the error function in its forming phase as can be seen in figure 2.2. Whether or not the estimated fit is significant will be tested using a t-statistic test.

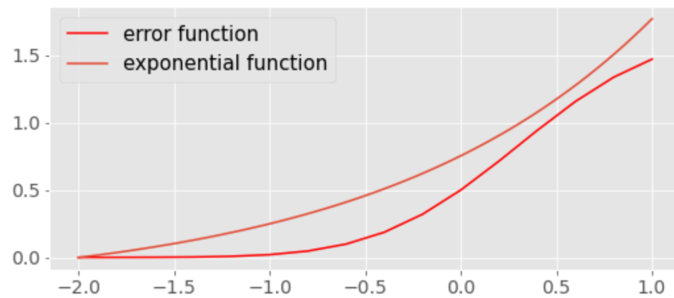


Figure 2.2: A drawn exponential and error function starting from the same point.

2.3.1 Regression model

The hypothesis of this research is that the relationship between the NPV and annual added wind capacity can be described by an error function. For simplicity, the error function is approximated using an exponential function. Using LS, the parameters for this exponential function will be estimated. The model to describe the relation between NPV and AAW is

$$y = AB^x + \epsilon, \tag{2.7}$$

in which y is the annual added wind, x the NPV and A and B are constants that will be estimated based on the data. ϵ is an error term. A least squares solution(LS) searches for estimates of A and B which minimizes the sum of the squares of the error term

$$\sum_i (y_i - \hat{f}(x_i))^2, \tag{2.8}$$

in which y is the annual added wind, x is the NPV and $\hat{f}$ is the estimated function. Using LS does give a valid result. But as can be seen in the results chapter, this solution gives more weight to the higher NPV's. This happens because the spread for the higher range NPV's is larger compared to the lower range NPV's. Therefore the LS solution is a correct solution, but not the best solution. To try and improve on the fit a slightly different model will be used. The model now becomes

$$y = AB^x e^{\epsilon^*}. \tag{2.9}$$

By taking the log on both sides this formula can be rewritten to

$$y^* = A^* + B^* x + \epsilon^*, \tag{2.10}$$

in which $y^* = log(y)$, $A^* = log(A)$, $B^* = log(B)$ and ϵ^* is an error term. The reason for formulating the model this way is that we can equate y^* to a linear term. This means it can be solved using OLS, which is a very straight-forward method to use. It is also a lot easier to find the p-values for a linear function. Changing the model to this log form also makes sense regarding the research question. This research focuses on the relationship between the NPV and the annual added wind capacity and how these variables influence each other. The actual numbers are less important.

The solution for both models seek to minimize the sum of the squares of the error term. Where they differ is how the error term is defined. In the model in equation (2.7) the error term is simply added and assumed to be evenly distributed for all NPV's. In equation (2.10) the error is assumed to be evenly distributed in the log-space. This will lead to slightly different results when estimating the parameters. Taking the log of a large number will decrease this number more, relatively, compared to taking the log of a small number. So the spread in the higher NPV's is decreased more compared to the spread for the lower NPV's. This means that the solution using equation (2.10) will put more weight on the lower values of y compared to the solution using equation (2.7). This choice and its implications will be further discussed in the Results and Discussion chapters.

By using OLS there are three assumptions made about the data[Stock et al., 2003]. The first of which is that the error term does not depend on x. This assumption is easily proven by saying that ϵ is normally distributed in equations (2.7) and (2.10). The second assumption is that the observations are independently and identically distributed, which is not the case in this research since the observations form a time series. This type of data The data is called a panel, meaning that multiple data points are taken over multiple points in time. Since the observations are made close to on another in time, correlation between data points is very likely. Also, the observations are made in the same five regions, which causes spatial dependence. The third assumption states that there can be no large outliers in the data, since this heavily influences the outcome of the estimated parameters. As can be seen in the results, there are no large outliers when looking at the NPV and the annual added wind capacity. Two of the three assumption have been met. Since the second assumption is not fully met, the results do need to be interpreted carefully. The p-values of the estimated parameters will probably yield better outcomes than in reality because of these dependencies.

The spatial and temporal dependence mentioned in the previous paragraph have to be taken into account when interpreting the results from the model. There are also ways to improve the results from this model using these dependence. For the spatial dependence so called pooled standard errors can be computed which take into account that pieces of the data come from the same region[Stock et al., 2003]. For the temporal dependence auto-correlation functions could be used to make predictions about the NPV or annual added wind capacity in the near future. Both of these methods are outside the scope of this research.

There are other ways to perform a regression analysis. Multiple regression analysis is a method that could also have been used here. This method allows for multiple parameters to be estimated. Using this method might have yielded more accurate results or allowed for reasonably accurate predictions over multiple parameters. The reason this method was not used is because room for error would probably be greater when trying to accurately estimate multiple parameters.

The upside of using LS over OLS is that $\hat{f}$ from equation (2.8) doesn't need to be linear. OLS has the advantage of being a more straight-forward method which can also be intuitively understood. LS will also be used to make a solution.

2.3.2 Calculating statistical significance

To be able to say anything about the statistical significance of the results, a t-statistic test will be performed from which p-values will be extrapolated. In order to be able to do these tests a fit will first have to be made through the data. This fit will be made using an exponential function.

The statistical significance of the data will be measured by comparing it to the fit made. Using a t-statistic the p-values with $\alpha = 0.05$ will be calculated. In which the p-value is the probability of getting test results with this outcome, assuming that the model proposed is incorrect. α is the significance level, and is defined as the value below which p has to go for the hypothesis to be accepted.

Chapter 3

Data

3.1 Data acquisition

For Germany, Denmark, Canada, Texas and Sweden for the years 2003 till 2020 the following data was needed for this report: Subsidies of wind electricity, capital costs of windmills, operation and maintenance costs of windmills, exchange rates and price indices, electricity price and electricity production. The complete list of sources used to gather the data for this research will not be mentioned in this report. Reason being that this would result in rather extensive tables with long url's. Instead, the data with all sources used for this model can be found in the link provided in this footnote [1].

3.1.1 Selection of countries

The selection of countries was mostly done based on the ability of finding enough and reliable data. This first led to the countries with the highest per capita wind energy installed. These are Denmark, Sweden, Ireland, Falkland Islands, Norway, Germany, Uruguay and Finland[WID, 2022]. Many of these countries were found to be unusable since there was not enough data available. Another important factor was the complexity of the subsidy regulations. A country like the Netherlands enough information available on its wind energy production, but its windmill subsidy regulations are far too complex for this research to reliably and easily use. Whereas other countries like Denmark and Canada use fairly

[1] https://docs.google.com/spreadsheets/d/1kfeJToB-yKKedgNsZBSFLGqeKovpT7Km/edit?usp=sharing&ouid=103750148791702724565&rtpof=true&sd=true

straightforward methods of subsidies per KWh delivered. Since this research focuses on large scale phenomena, the very small countries were left out. Denmark is the smallest country of the five countries chosen for this research. The reason this country was used is that it does have one of the biggest per capita wind sectors in the world. Also their long history with wind technology always makes Denmark an interesting country to look at (The three-bladed windmill now seen all over the world is actually called the Danish design!). As will be seen in the results, the relative small size of Denmark is reflected in its fluctuating data, more on that in the discussion.

3.2 Data quality

There is an abundance of data to go around on the topic of wind energy. This results in most of the data being used in this research being of conventionally trusted sources like the International Energy Agency(IEA) and the international renewable energy agency(Irena). Unfortunately, not every single data point found could be found. Eventuallt about 20% of the data had to be estimated using other data points. An example being the capital costs for Germany in the years 2009, 2011, 2013 and 2014 which were estimated using data from previous and future years. It must also be noted that it was not possible to work with uncertainty measures, as nearly all of the sources did not provide any. Therefore one must keep in mind that this data and results have an unknown margin of error. How the data quality influenced the results is mentioned in the discussion.

3.2.1 Subsidies

For the subsidies of countries a lot of information was gathered from government websites themselves. The German, US, Canadian and Swedish government provided a lot of info. For Denmark two reports by the IEA and the Global Wind and Energy Council(GWEC) were used[EIA, 2012][Council, 2017]. One of the issues encountered into whilst doing this research was the lack of definition when being presented with numbers on subsidies. Subsidies can be very differing in form, shape and size. Who gets the subsidies, at what point in time, for what part of the operation and for what period of time can all influence the subsidies policy. The many different and complex subsidy rules were actually the main reason that the Netherlands was not used for this model. To keep this model as simple and free of mistakes as possible simple subsidy systems were one of the main requirements for a country to be used in this model.

3.2.2 Capital costs

For capital costs reports by Irena were mostly used for Sweden, Germany, Canada and Denmark [Irena, 2012]. For Texas a report by the US government was used, which also means that these capital costs are estimations taken from data about the US as a whole [$US_{g}ov$, 2021]. Since Texas is one of the largest producers of wind energy in the US this assumption was assumed to be safe. For capital costs, like other variables that follow some of the data had to be estimated for lack of literature. These estimations were largely made based on the data from similar countries and data from a different time period.

3.2.3 O&M costs

For O&M costs a lot of data for Denmark, Germany and Sweden was obtained from an IEA technical report from 2018[IEA, 2018]. A very notable lack of data was found in the O&M costs of Canada, virtually no literature could be found on this topic. To compensate, data from the US was used to estimate these costs for Canada. Finding data for O&M costs presented with a similar problem found in the subsidies data. There were widely ranging definitions for what covers O&M. This problem made a lot of the papers on this topic unusable for their differing definitions. This was one of the main reasons for using mainly the IEA report.

3.2.4 Exchange rates and price index

For the exchange rates data from the ECB was used. The price indexes were all taken from the government websites. Seeing as these numbers are all fairly well documented and non-controversial, no other literature was used.

3.2.5 Electricity price and production

For the European electricity prices the data was taken from Eurostat, the statistical goldmine for data from the European Commission. For Canadian and Texas prices, the EIA was used as a source[EIA, 2022] . For electricity prices the same problem arose as for O&M and capital costs. The problem being that there are very much differing definitions of what electricity price encompasses.

To account for these differing definitions some scaling had to be applied to found data. An example is the electricity price in Denmark from 2007 to 2014. The source used for this data gives the electricity price paid to the energy supplier and electricity network combined. Literature tells us that about 55% of this electricity price goes to the energy supplier, allowing a fair estimation to be used in this model[EIA, 2021][BDEW, 2022].

For electricity production data was pulled from the IEA, Irena, the US government and ourworldindata.

Chapter 4

Results

In this chapter, the individual results for all parameters of equations 2.1 and 2.4 are presented and discussed. Further on, general remarks are made on the method and model and the individual countries and their national influences on the results are discussed.

4.1 Net present value

The findings of the parameters for the NPV are presented in figure 4.1. Similarly to the previous chapters, all findings in this chapter have been expressed in real 2020 euros.

4.1.1 Intermediate results

The subsidies are presented in figure 4.1a. Here we see a vast difference between Germany and the countries which can be mostly attributed to very differing systems. Germany for example has a variable FIT-price. A FIT-price means that sellers will gain a predetermined price for their electricity. Sweden has a quota system with green certificates in which companies have to use green energy but in which the market determines the price of these green cetificates[Vagero, 2019]. Denmark, Texas and Canada all have slightly different forms of a simple subsidy in which energy suppliers get money for each KWh of electricity they deliver. It can be noted that especially for Germany and Denmark subsidies have been falling throughout the years. Recently Germany has chosen to lower its subsidies because of climbing energy prices [Wacket, 2021], with Denmark choosing to directly give money to households to support them in these expensive times[Buttler, 2022]. On the longer term this trend of lower subsidies can be attributed to an ever better faring wind market[GTM, 2017]. In theory, this reduction in subsidies should be offset by lower costs and a higher electricity price.

The electricity prices are presented in figure 4.1b. A price increase in Canada and Texas can be found around 2008. This could correlate with the increase in natural gas price in 2008, which makes up about 20% of the electricity prices. The electricity prices have also fallen following the huge drop in natural gas prices in the US after 2008.

Capital costs, as presented in figure 4.1c seem to follow a worldwide(as far as these five countries can be seen as a representation of the world) rise and fall of capital costs. This could be linked to the worldwide supply shortage of the time. Though the price of construction materials like steel don't seem to follow the same trend. As the data only goes till 2020 the recent shortage in construction materials has not been taken into account yet.

Operation & maintenance costs(O&M costs), as presented in figure 4.1d show to be very much stable for the European countries. In which the American countries do show numbers of about 3 times as high in 2001, though later declining to roughly the same levels. This huge difference could be attributed to a knowledge difference. European countries(most notably, Denmark) have a longer history with wind energy and could therefore have more knowledge about smartly building and maintaining their windmills.

4.1.2 Average outcomes

In figure 4.2 the average NPV division for each country is presented. What is immediately noticeable is the positive NPV for the European countries and the low and even break-even NPV's for Texas and Canada. This can be mostly attributed to lower subsidies and higher O&M costs. The decommissioning costs are hard to make out in this figure, because of their minute influence. These costs average out to €0.25/MWh, rising and falling a bit with the expected windmill lifetime. Making its contribution about 0.5% of all NPV attributions. The O&M costs for Texas and Canada are relatively high, contributing to about 20-25% of all NPV contributions. It is possible that these are over-estimations since the same costs in the European countries are considerably lower. Even with O&M costs closer to the European countries, Canada and Texas still would have much lower NPV's.

4.2 Added wind capacity

In figure 4.3 the added wind results are presented as discussed in equation 2.4. In figure 4.3a the total electricity generated per year can be found. Most countries are very stable in their total electricity production. Over the period of 2008-2020 the electricity production of Denmark and Germany decline about 10%, Canada increases about 2%, Texas sees an increase of about 17% and Sweden an increase of 10%. Though these numbers do very much vary when looking at different intervals.

The added wind capacity in figure 4.3b looks at the added installed wind installation in each country in MW. Germany can still be seen to be a major player in this field, though dropping in the past few years.

Figure 4.3c presents the real interesting numbers, the normalized added wind capacity. In this figure the annual added wind capacity from subfigure b is divided by the total electricity generated in that year from subfigure a. Denmark takes over from Germany in most annual wind installations in this figure, though the results do fluctuate a lot. This is mostly due to Denmark being a relatively small country in which one big wind farm can already heavily influence the amount of wind energy generation capacity being added in a year.

4.3 Final results

The final results of each individual country are presented in figures 4.5 and 4.6. From these figures there is some correlation visible between the NPV and the annual added wind capacity. Canada and Sweden have a brief period, from 2013 till 2018, in which some overlap between the two variables can be found. A general trend in these two figures is that the NPV starts of high and starts to decline. As will be discussed later this can be attributed to relatively high electricity prices and low capital costs.

In figure 4.4 the final results are presented. In this figure the results from figure 4.3 are compared to those of figure 4.1. It's important to note that the NPV of each year is calculated using numbers from five years prior. As explained in the Method chapter there is a discrepancy between a plan for a windmill being put to work and it actually being delivered. To account for this difference the NPV for 2008 is estimated using data from the years before. The annual added wind capacity presented is made using data from that year. The direction in which all countries seem to go is also noticeable. Starting in 2008, all countries seem to eventually wonder to a lower NPV and often higher annual added wind capacity. This can partially be attributed to the electricity prices being high in the years preceding 2008.

To test the hypothesis two exponential fit functions were fitted to the results. These exponential functions were used as an estimate for the error function (equation 2.6). These two fits differ in their error term, as explained in the Method chapter. What is notable is that the fit using ϵ^* (Which came from the OLS solution) seems a better fit for the low range NPV's(-5 till 10 €/MWh) compared to the high range NPV's(above 10 €/MWh). This makes sense, seeing as the default OLS will put more weight on ranges with a bigger spread, since it looks at the squares of the error term. When taking the log of ϵ the larger error terms are reduced more compared to the smaller error terms, because of the way log works. There is a larger spread in the high-range NPV's which also could indicate a larger error term. Because of these two reasons, this research will continue working with the fit using the OLS solution and ϵ^*.

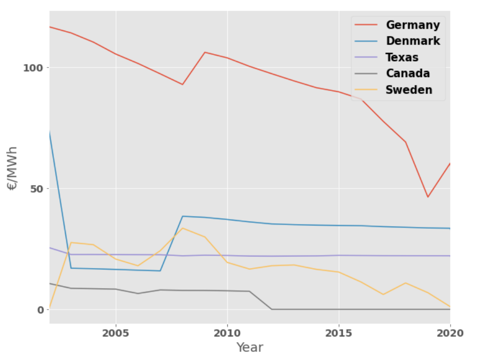
To find the p-values as mentioned in the method chapter a t-statistics test was performed on the data with the fit. From this test a p-value of 0.76 was found for A and $4.85 * 10^{-11}$ was found for B, which are the estimated parameters in equation 2.7. Using $\alpha = 0.05$ A is not statistically significant, while B is. This result shows there is an exponential relationship between NPV and Annual added wind, while the linear component cannot be proven from this data.

4.3.1 Using different normalisation

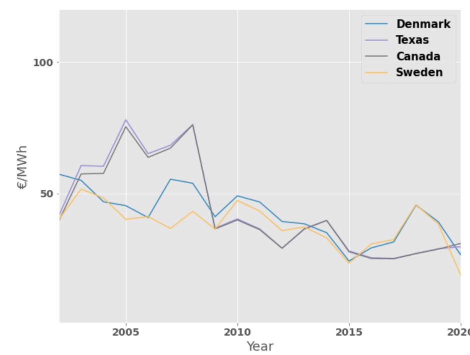
In this research the added wind capacity has been normalised using the total amount of electricity generated in a country. This method was chosen for multiple reasons explained earlier but obviously also has some drawbacks. Two similar countries in size and economy can have very different energy production due to factors like natural resources and trade with neighbouring regions. Germany and Texas are a good example in which Texas has a per capita electricity production which is about two times as high as Germany. In this section the total wind capacity is taken as the normalisation factor to see how much the results are affected. The formula for annual added wind capacity then becomes

$$\text{Annual added wind capacity} = \frac{\text{Annual wind electricity installation(MW)}}{\text{total wind electricity capacity(MW).}} \tag{4.1}$$

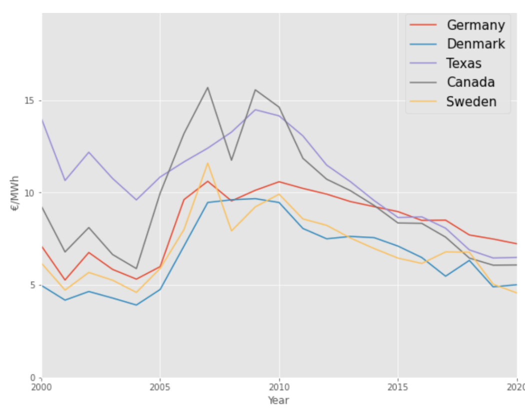
The results of this endeavor can be found in figure 4.8. In 4.8c we can see that there is still no real correlation between the two variables. To understand this figure it's important to understand that the NPV values are the same as in figure 4.4. Only the y values have changed to those in figure 4.8b. Sweden and Canada seem to score much higher annual added wind compared to the original result. This can be partly contributed to the fact they have relatively low amounts of wind capacity. Which means that building a few wind parks can already give an annual added wind factor of up to 30%.



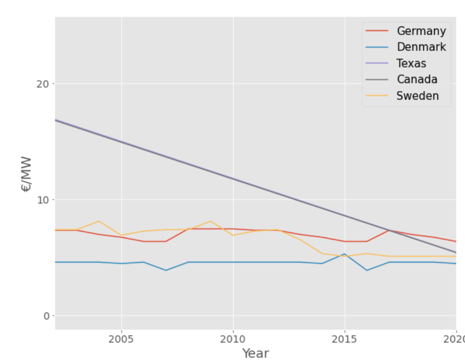
(a) Subsidies in €/MWh plotted over time.



(b) Electricity price in €/MWh plotted over time. Germany is not included as the electricity price is taken together with subsidies in a.



(c) Capital costs in €/MWh plotted over time.



(d) O&M costs in €/MWh plotted over time.

Figure 4.1: The data found for the four main components of the NPV as described in equation 2.1 for the five countries.

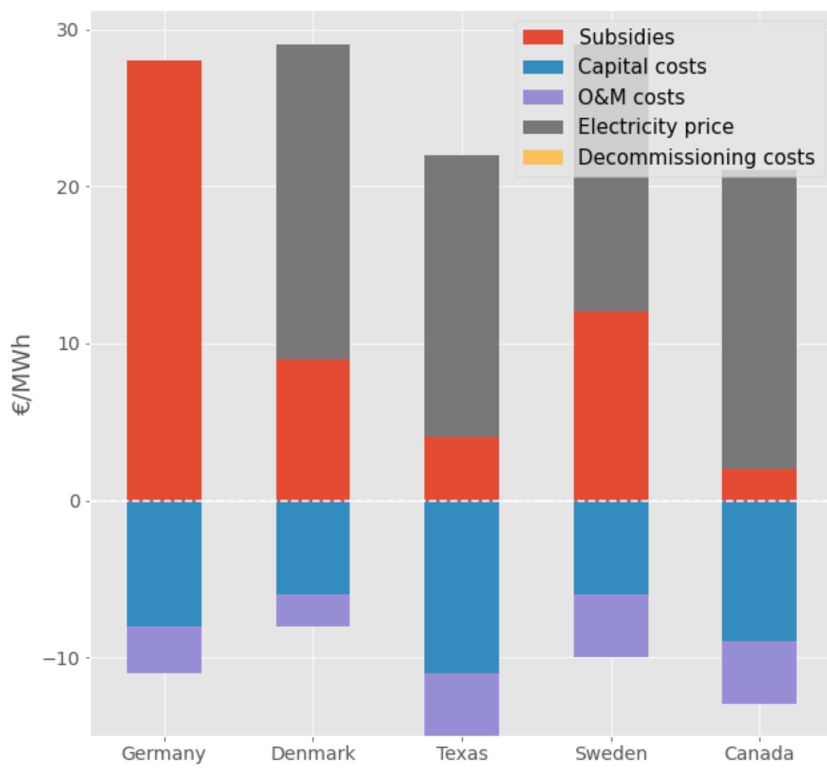
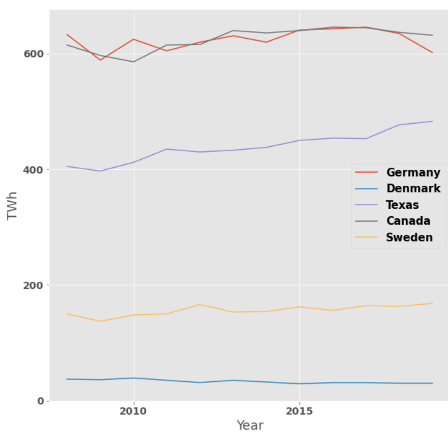
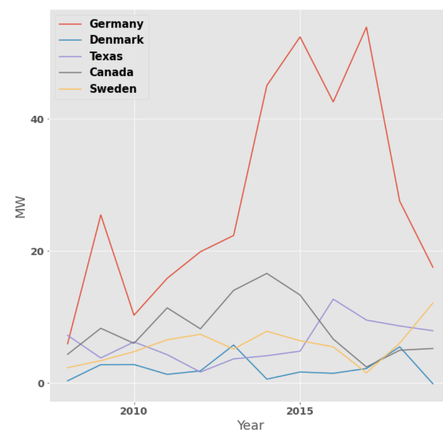


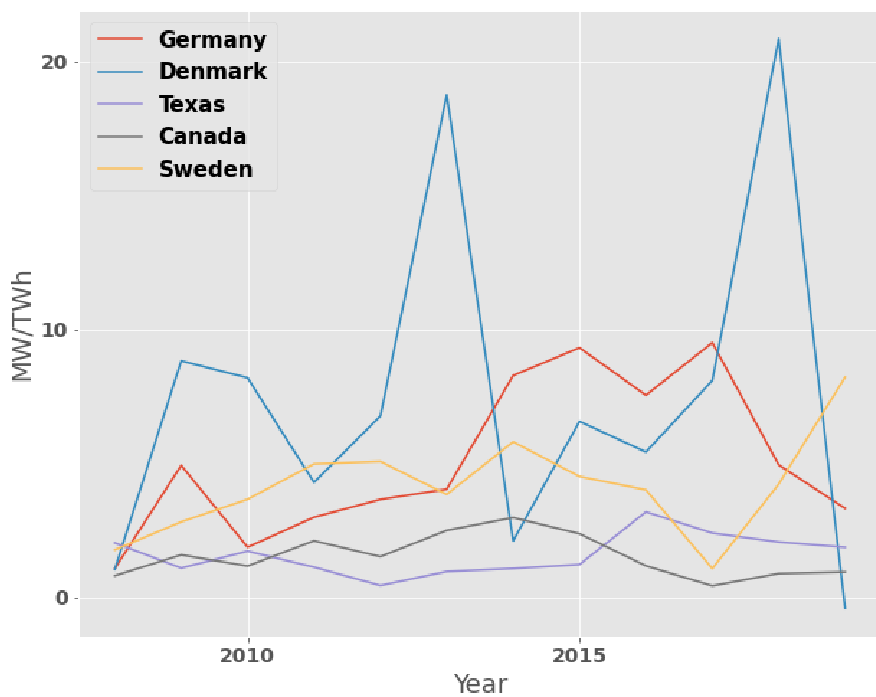
Figure 4.2: The average NPV division for each country over the years.



(a) The total electricity generated per year.



(b) The added wind capacity per year.



(c) The normalized added wind capacity per year.

Figure 4.3: Data from the three main components from equation 2.4.

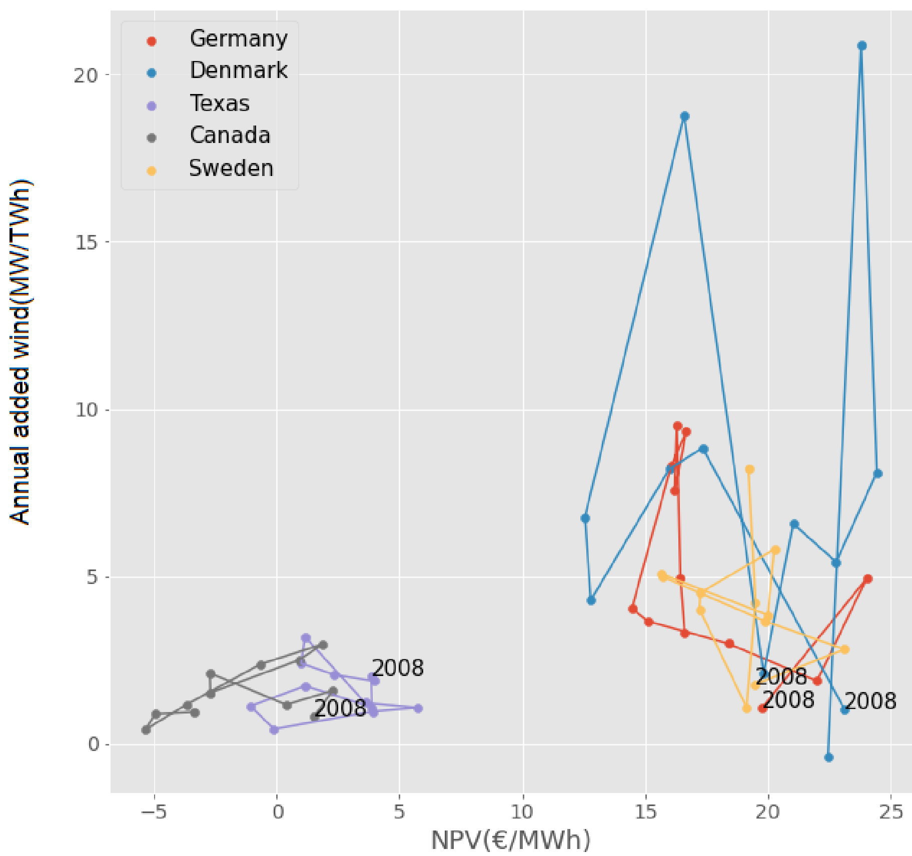
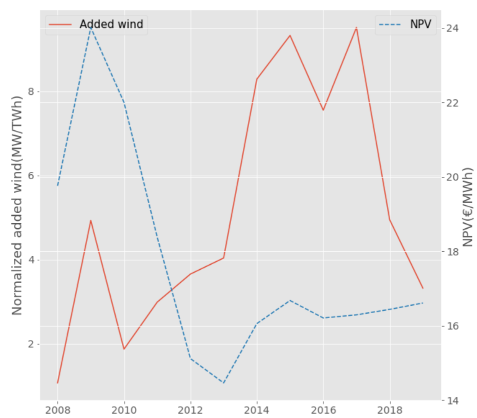
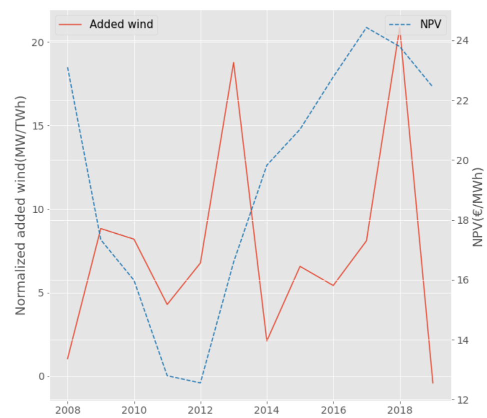


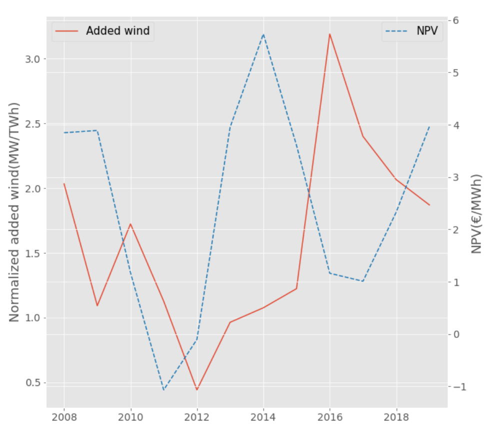
Figure 4.4: Final result of this model. NPV is plotted against the annual added wind for each country.



(a) Germany

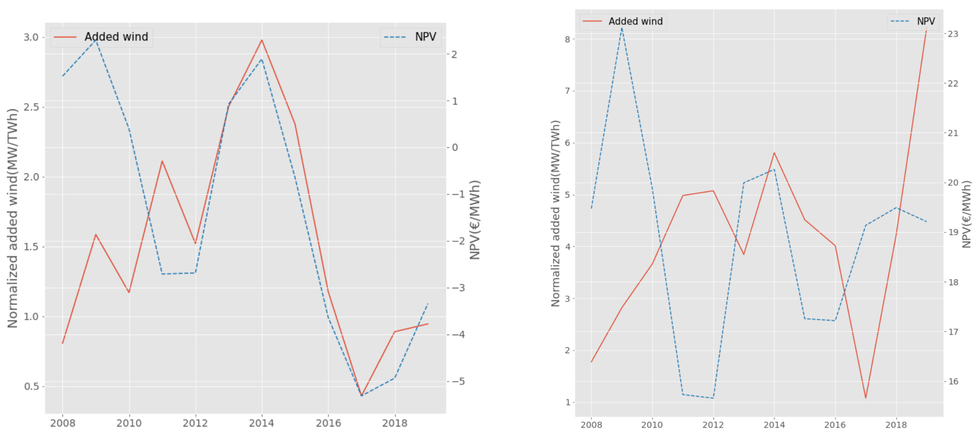


(b) Denmark



(c) Texas

Figure 4.5: NPV plotted with annual added wind capacity.(1/2)



(a) Canada

(b) Sweden

Figure 4.6: NPV plotted with annual added wind capacity.(2/2)

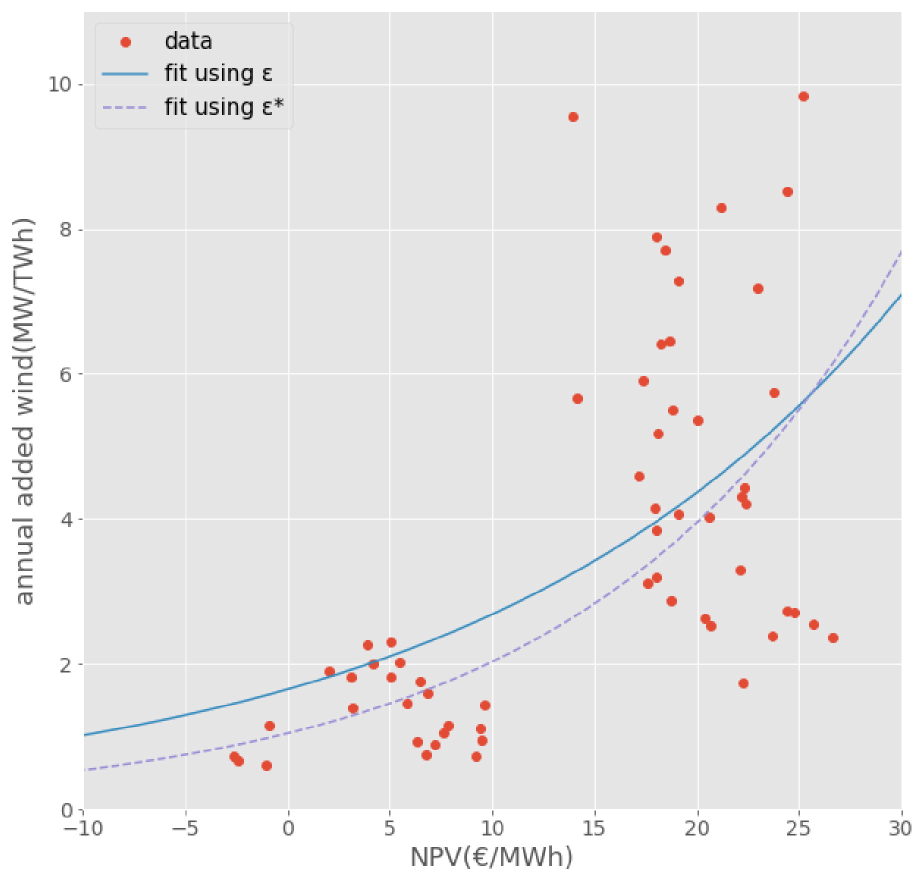
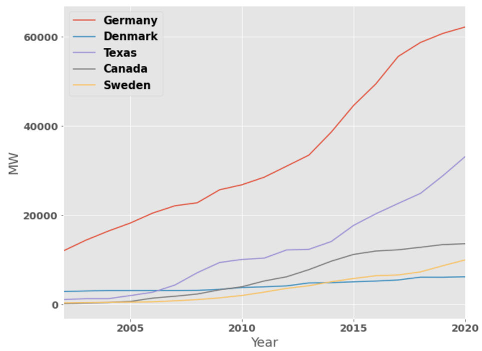
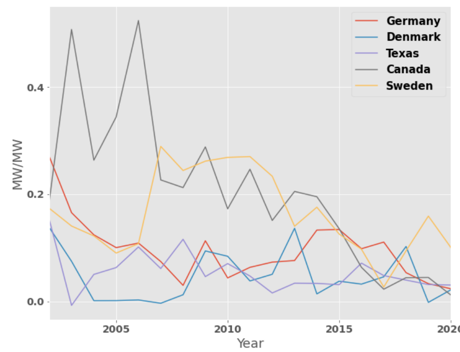


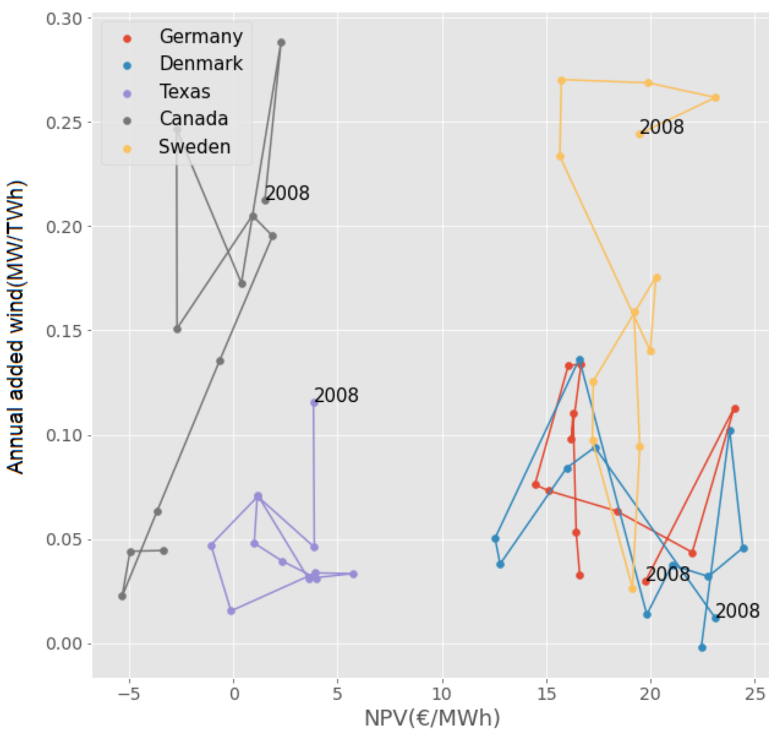
Figure 4.7: Exponential fits drawn through the final results. ϵ and ϵ^* are the error terms from equations 2.7 and **??** respectively and represent the LS and the OLS solutions.



(a) Total wind capacity installed



(b) Normalised annual added wind capacity.



(c) NPV against the normalised annual added wind capacity.

Figure 4.8: Final results using the existing wind capacity as a normalisation factor.

Chapter 5

Discussion

5.1 General remarks

The financial relationship between NPV and annual added wind capacity is not a perfect causal relationship. There are many types of biases present which can have and probably will have influenced the result. This is not to say that the results are useless, but it is a caution to hang too many conclusions on them. One of the biases that can be found in this research is hidden in the relationship between capital costs and the added wind capacity. As more windmills are build, the capital costs will drop because of learning by doing and scaling efficiencies. Vice versa, when capital costs drop it becomes cheaper to build windmills so more will be build.

Another bias that occurs deliberately in this research is about the omitting of variables that could have influenced the results. Multiple factors like local regulations, permits, cultural influences, willingness of a country to switch to green energy, costs and availability of land and the costs of capital are all not taken into account.

This research also assumes the NPV to influence the amount of wind energy being build. What can be seen in countries with a high population density is that land area can become very valuable. This is one of the reasons, if not the major reason, that Denmark has always built offshore wind parks as part of their wind generation. As more and more land and sea have been build full, further away or harder to reach locations will have to be used to build the next generation of windmills. This means that an increase in windmills can decrease the NPV.

5.2 Statistical significance

To check whether there was any exponential relationship between the NPV and the annual added wind an OLS was performed to make a fit. The data was then checked for statistical significance regarding this fit using the t-statistic. It has to be noted that this also creates a form of bias since the fit was made using the data, allowing for a higher p-value than would have occurred with an only theoretical model. Though this bias does exist, it is still evident that there is a strong exponential relationship between the two researched variables. What will also have influenced the p-value are spatial temporal dependence. Since the data is taken from five countries over multiple years, so called clusters of data have formed, as can be clearly seen in the final results. This happens because countries often do not change much over the years. Meaning that data from a country from one year is often strongly correlated with the other years. There are ways of correcting standard errors for this bias, though they can become rather complex. A recent study by [Abadie et al., 2017] also pointed out how these clusters and how to deal with them is often more complex than assumed. Finding and implementing the correct method for dealing with these clusters has therefore been left outside the scope of this research. For now, we simply have to keep in mind that the real p-values are higher than those found in this research.

Two fits were made using slightly different methods as mentioned in the Method chapter. One solution used Ordinary Least Squares(OLS), the other used Least Squares(LS). The difference between these two mostly being the error term that is used. The solution made using LS assumed a regular error term, the OLS solution assumed a normal distributed error term in the log space. This tells us that as we look at larger NPV's, ϵ^* will become relatively smaller compared to smaller NPV's. In practice, this means that the fit made using ϵ^* will be less sensitive to spreads in the higher NPV range. Whether this is correct or not is really a choice, as arguments can be made for both forms. Using the original ϵ gives results that are closer to the data using the assumptions made for OLS. But as can be seen in figure 4.4 the OLS fit made using ϵ^* gives a better fit for the lower NPV values. In this research the OLS fit using ϵ^* was chosen to be used, as this yielded a better fit for the lower value NPV's.

5.3 Sensitivity analysis

To check the influence of certain variables and assumptions made a brief sensitivity analysis has been performed. The results of these analyses are not presented in this report for they do not show any new insights or information.

5.3.1 O&M costs

As can be noted in figures 4.1d and 4.2 the O&M costs for Texas and Canada are much higher in the early 2000's than the other countries. This difference can have multiple causes, Wiser et al. [2019] mentions that there are vast differences in estimated costs across literature. This difference is notable and can possibly be explained by differing definitions of O&M costs. What is and what is not taken into account could differ very much per research leading to this difference. In terms of the model lower O&M costs for Canada and Texas would have changed the final outcome. But the model still would have resulted no significant outcomes.

5.3.2 Time lag

One of the main assumptions in this model is the use of time lag. As mentioned before a time lag of five years is used in this model to account for the difference in time between deciding on windmill building and the actual final delivery of the windmills. One could think that one of the reasons for the inability of the model to provide any correlating answers could lie in this time lag. Reasons being that the time lag can vary greatly over time, between countries and even within countries. Furthermore there is not one clear definition of the period this time lag covers. To try to find out if a different time lag conjures up any different results multiple different time lags have been tried for this model. The results showed very similar correlation to the original results and no other significant differences could be found. For future research it might be interesting to dive into the mechanics underlying this process. Not in the first place to make a more sound economic model. But mostly to gain insight into the decision making and execution process underneath the building of wind energy.

5.3.3 Expected windmill lifetime and yearly electricity price

Two other variables for which assumptions were made(though based on findings in literature) are the expected windmill lifetime and the expected yearly electricity price increase. The model has been run several times with a 20% margin for both these variables separately from each other. The model yielded either very similar but mostly worse correlation between the annual added wind and the NPV. It is difficult to say how good the original estimations for these variables were, but choosing different ranges for them does not tell us anything more. This model also used the assumption that 55% of all electricity revenues go to the contractor. There is uncertainty in this assumption as different countries with differing situations will divide this money differently. What's more, the different sources used could have used slightly differing metrics for calculating the revenue.

5.4 Policy implications

This section tries to give some insight into the possible lessons policy makers might take from this research. First general remarks on policies are made. In the sections below, individual comments for each country will be made. One of the main-takeaways from this research for policy makers has to lie in the effectiveness of subsidies. From this research and especially looking at figure 4.4 it can be concluded that on average an increase in NPV leads to an increase in the amount of wind energy build. The rate of NPV over increase in windmills differs depending on the NPV. For Texas and Canada an increase in NPV would be only partly as effective as an increase in NPV for Germany, Sweden and Denmark. This is not to say that Texas and Canada have nothing to win with an increase in subsidies. What it does tell us is that their expectations have to be managed. What's further interesting to note is how there seems to be a general decline in subsidies in Germany, Sweden and Canada. It will be interesting to note in a few years time how this has affected the building of windmills.

A factor that has not been taken into account in this research is the (indirect)effect of policies on the building of windmills. An example of this would be the ETS system in the EU. This system has increased the need for renewable energy, and possibly will do even more so in the future. This prospected increase could be one of the reasons why the European countries have started to decrease their subsidies. Since they are expecting an increased demand for green electricity.

5.5 Trends in individual countries

In the previous section the results as a whole were discussed. In this section more focus will be put on the interesting aspects of the individual countries that were not covered in the previous section.

Sweden

Starting of with Sweden, it differentiates itself with its subsidy system. Sweden relies on an electricity certificate market which it is shares with Norway[SEA, 2020] which produced around 95% of its electricity from hydro-power till 2015, after which wind power became more prominent[Dorber et al., 2018]. In Sweden, currently about 17% of electricity comes from wind power. This form of subsidies will surely have many advantages. But for this research it does mean that the subsidies received in Sweden are also influenced by the Norwegian electricity production, creating a form of bias. What might also have been an influence on the Swedish wind market are indigenous people. In 2019 the highest environmental court of Sweden authorized the building of a 500MW wind-park in Pauträsk[Cambou et al., 2021]. These lands have been protected for decades because of their cultural values, its nature and its importance in the field of Reindeer husbandry. This battle between energy companies and local communities together with environmental groups has seen many winners and losers on both sides. Which over the years has had a direct impact on the building or withholding of wind parks across Sweden. Sweden is planning on increasing its production of wind energy. Where Sweden produced 19TWh in 2020 they are planning to produce 50TWh in 2040 [Sweden, 2022]. This equates to about 3.5GW of added wind power per year. If Sweden were to reach those goals they would have to nearly triple their current building of windmills for the next 20 years4.3b. Seeing as their subsidies and NPV already are higher than the other countries, an increase on this side might not be the main way to go. A well thought plan from the government, including permits, possible locations and regulations is probably necessary to provide for this ambitious though necessary goal.

Germany

When looking at the final result in figure 4.4 Germany starts of with an NPV of around 34 €/MWh, which then falls in the following years. Around 2013 the annual added wind capacity starts to rise but falls again after 2016. The high NPV starting in 2008 can for a large part be attributed to relatively low capital costs in the years 2003-2007. The fall in added wind capacity after 2016 is remarkable, since this seems to overlap with some major renewable energy reforms around 2010. One explanation for this fall is the inability of the transmission network in Northern Germany to keep up with the rapid changes in energy supply, severely slowing the building of new windmills[Oltermann, 2016]. Another important possible factor in the decline of windmills being built is a falling acceptance rate. Fear of infra-sound and not being (un)able to participate also play significant roles in the (non-)acceptance of new windmills in Germany[Langer et al., 2018]. Germany is planning on scaling up its onshore wind energy from 50.5GW in 2017 to 81.5 in 2030 [Germany, 2022], which necessitates an annual increase of about 2.4 GW of wind energy per year. As can be seen in figure 4.3b Germany has recently had a fall in its annual production. As mentioned before in this paragraph, slow progress in the transmission network is one of the key factors in this. Germany has proven that they are able to build windmills at a much higher rate than they are currently aiming for, though good government planning is essential.

Denmark

Denmark is interesting, for it is the smallest country in this list. But over the years it has made a name for itself as one of the pioneers in renewable and most notably wind energy. The Danish company Vestas being an example as the world's largest wind-turbine manufacturer. The NPV and annual added wind capacity in figure 4.4 seem to follow no other pattern then randomness in a specific boundary. These fluctuations can be partly explained by Denmark being a relatively small country combined with the usual scale of wind parks. When a wind park is of 100MW is finished it can single handedly account for about 50% of the added wind capacity. Export of wind energy is of major importance to the Danish economy. Which means that Denmark can profit from subsidies in the wind energy sector in multiple ways. First of is the increase in wind energy in the country itself as discussed in this research. A secondary effect is an increase in the country's wind energy export. Denmark is planning on having 7.8GW of installed wind energy in 2025 compared to 5.1GW in 2015[IEA, 2017] . Denmark's annual added wind averaged out to about 225MW per year since 2015 4.3b. If Denmark keeps us this pace they will just about miss their target goal by 0.5GW. In the 3 years Denmark has left it will be difficult to ramp up their wind energy production. It is difficult to say whether and how much an increase in NPV will effect the building of windmills. Since Denmark is the country with the most fluctuating final results4.4.

Canada

Canada is the country with the lowest NPV, even going negative at some point. This corresponds to low annual added wind capacity not going over 2.5% of the total electricity production. From figure 4.2 it is clear that low subsidies and high O&M costs have a large role to play in this. A subsequent explanation for these high costs and low subsidies may lie in the political withholding in wind energy. A mixed literature study and survey found that the politicizing of wind energy in Canada has made the subject very much unpopular in local communities[Walker et al., 2018]. This does contrast with other studies that find Canadians are willing to pay 14% extra to be able to use wind energy[Koto and Yiridoe, 2019]. Canada has the goal of having 90% of their electricity come from 'non-emitting' sources by 2030, like hydro, wind, solar and nuclear power[Canada, 2022]. No mention is made of what share each power source will have to provide. Currently, 80% of Canada's electricity is already coming from these non-emitting sources. With Canada's total electricity generation sitting around 660 TWh, an increase of about 66TWh would be necessary. If Canada were to try to reach this goal using only wind power they would need to build a total of 7500MW worth of wind power. This would equate to delivering 837MW of wind power per year. Canada delivered an average of about 450MW per year of wind energy over the past five years. If Canada were to keep up this pace. and not change their total electricity generation they would only need to have 54% of their added electricity capacity from windmills, which seems very doable.

Texas

Texas is interesting in its own right for its rich history of energy production. Being a leader in gas and coal production throughout US history and now being one of the leading states in wind energy. When looking at figure 4.4 Texas seems to lag behind the European countries both in terms of NPV and annual added wind capacity. The low NPV can, similarly to Canada be attributed to low subsidies, high capital and O&M costs. It seems that Texans are not so much against wind energy, most are even in favour[Swofford and Slattery, 2010]. What has to be made clear is that Texas does not produce small amounts of wind energy. It simply produces a lot of other types of energy as well. When looking at total electricity generated, Texas produces about 70% as much electricity as Germany. Even though Germany has about 3 times as many inhabitants as Texas. Therefore the low annual added wind capacity of Texas can partly be attributed to the metric used. In terms of goals, Texas had set a goal to achieve 10GW of renewable power by 2025. Though they passed this goal in 2009 already, using mostly wind power[IEA, 2022].

Chapter 6

Conclusion

In this research a simple model was made to compare the net present value (NPV) of wind energy to annual added wind capacity for Germany, Denmark, Texas, Sweden and Canada.

In this research an exponential relationship was found between the NPV and the annual added wind capacity. A 10% increase in NPV($€/MWh$) found an increase of 15% for the annual added wind capacity(MW/TWh) of added windmill capacity per TWh of electricity produced.. An analysis of the five countries did reveal significant differences between the individual components of the NPV. Though results vary some global trends can be found. Big differences were found between countries as to their NPV and annual added wind capacity. A sensitivity analysis found no improved results when using different assumptions for factors like windmill lifetime and future expected electricity price. The low p-value can partly be explained by biases in the data, the effect of clustering of countries was not taken into account. One of the big limitations of this study is its reliability on a broad range of data sets. With each data set offering its own definitions, ranges of error and time periods covered there is considerable room for error. Furthermore, there are many factors in this model that influence each other in some shape, way or form. An example being lower capital costs which can lead to more windmills being build because of demand-supply effect. This increase in windmills can than lead to lower capital costs because of learning-by-doing effects. In literature there is an ongoing search to find out what the process are that influence the growth of the wind energy industry. This research shows that a simple economic model is not enough to predict how much wind energy capacity a country will build in the future. There are many factors which have, consciously, not been taken into account when building this model. These factors include, but are not limited to, cultural influences, permits, local interference and the failure of the transmission networks to keep up. We can conclude that these non-economic factors have a substantial role to play in the development of the wind industry. Future research could try to focus on further understanding the workings behind the decision making for windmills. Social, political and cultural aspects could for example be combined with an economic model.

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