TECHNISCHE UNIVERSITÄT WIEN

Diplomarbeit

The future development of marginal CO2 abatement costs for Wind and PV in the power sector in Germany

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs

unter der Leitung von

Univ.Prof. Dipl.Ing. Dr. Reinhard Haas
(E370 Institut für Energiesysteme und Elektrische Antriebe, Bereich: Energiewirtschaft)

eingereicht an der Technischen Universität Wien

Institut für Energiesysteme und Elektrische Antriebe

von

Richard Löw, BSc.

1228326 (066 506)

St.Veitgasse 56/2/2

1130 Wien

Wien, im Jänner 2019

Richard Löw

TECHNISCHE UNIVERSITÄT WIEN

Ich habe zur Kenntnis genommen, dass ich zur Drucklegung meiner Arbeit unter der Bezeichnung

Diplomarbeit

nur mit Bewilligung der Prüfungskommission berechtigt bin.

Ich erkläre weiters Eides statt, dass ich meine Diplomarbeit nach den anerkannten Grundsätzen für wissenschaftliche Abhandlungen selbstständig ausgeführt habe und alle verwendeten Hilfsmittel, insbesondere die zugrunde gelegte Literatur, genannt habe.

Weiters erkläre ich, dass ich dieses Diplomarbeitsthema bisher weder im In- noch Ausland (einer Beurteilerin/einem Beurteiler zur Begutachtung) in irgendeiner Form als Prüfungsarbeit vorgelegt habe und dass diese Arbeit mit der vom Begutachter beurteilten Arbeit übereinstimmt.

Wien, im November 2018

Richard Löw

Danksagung

Mein besonderer Dank gilt meinen Freunden, meiner Familie, insbesondere meiner Mutter Helga, die mir mein Studium ermöglicht hat, und nicht zuletzt meiner Freundin Tina, die mich immer unterstützt und motiviert haben, selbst als mein eigener Antrieb weniger geworden ist. Ohne sie wäre es wesentlich schwieriger geworden, diese Arbeit und dieses Studium zu absolvieren.

Besonderen Dank auch an Dr. André Ortner, der mir über den längsten Zeitraum der Verfassung betreuend und beratend zur Seite stand und mein persönliches Interesse an der betrachteten Thematik immens fördern konnte.

Ebenfalls bedanken möchte ich mich bei Prof. Reinhard Haas, dessen Feedback mir sehr geholfen hat und ohne welches diese Arbeit nicht geworden wäre was sie ist. Besten Dank auch für die Unterstützung in jeglichen organisatorischen Belangen durch das Dekanat, insbesondere Fr. Dietlinde Egger.

Kurzfassung

Diese Arbeit legte ihren Fokus auf die Entwicklung von marginalen CO2-Vermeidungskosten von Wind Onshore, Offshore und Photovoltaik (PV) im Stromsektor Deutschlands bis 2050. Die Grundstruktur der Arbeit gliedert sich in zwei Teile: Zum einen eine Literaturrecherche, die Studien aus der Vergangenheit beleuchtet, die sich mit der Thematik der Vermeidungskosten der betrachteten Technologien befassen. Zum anderen wurde ein Modell entwickelt, dass eine mögliche Entwicklung der Vermeidungskosten bis 2050 zeigt, und diese mit CO2-Preisszenarien vergleicht.

Ein MATLAB Modell zur Lösung eines Optimisierungsproblems wurde verwendet, welches fossile Stromerzeuger Kohle, CCGT und OCGT als Variablen verwendet, bei einer vorgegebenen Einspeisung erneuerbarer Energieträger. Die Vermeidungskosten wurden bestimmt, indem die Einspeisung um 10% erhöht wurde, während der Bedarf und der fossile Strommix gleich blieben. Die Unterschiede bei CO2-Emissionen und Marktwert des Stroms pro MWh, ebenso wie die Stromgestehungskosten, sind die Grundlage für die Berechnung für die Jahre 2020, 2030 und 2050.

Die Kosten für Wind Onshore betragen 2020 150-300 €/tCO2, und fallen bis 2050 auf about -50 – 100 €/tCO2. Wind Offshore entwickelt sich von 200-300 €/tCO2 im Jahr 2020 bis 50-80 €/tCO2 in 2050. PV sinkt von 150-500 €/tCO2 in 2020 auf negative, daher in jedem Fall wirtschaftliche, -100 - -50 €/tCO2 im Jahr 2050.

Table 1: Ergebnisse der Vermeidungskosten von 2020-2050

in €/tCO2	2020	2030	2050
Wind Onshore	148.73 – 308.91	265.20 – 107.94	-53.90 – 100.66
Wind Offshore	200.53 – 309.39	255.78 – 146.26	45.52 – 82.47
PV	200.10 – 491.68	145.22 – 394.18	-98.27 – -35.48

Zu Beginn des untersuchten Zeitraumes befinden sich alle Vermeidungskosten weit über dem Niveau der CO2-Zertifikate. Die weitere Förderung der Technologien ist daher gerechtfertigt und notwendig um einen Ausbau voranzutreiben. Ohne die Unterstützung wäre eine Transformation des Energiesektors in ein emissionsarmes System und die Erfüllung der klimapolitischen Vorgaben kaum realisierbar, da keine der betrachteten Technologien in naher Zukunft wirtschaftlich wird.

Eine optimistische Schätzung für den CO2-Preis vorrausgesetzt, wird als erste Technologie ohne zusätzlichen Support PV zwischen 2030 und 2035 den Punkt erreichen, an dem die Einkünfte des Emissionshandels die Ausgaben der Förderung ausgleichen.

Die Kosten für Wind Onshore könnten nach 2035 eine gesamtwirtschaftlich positive Bilanz aufweisen, bei einem CO2-Preis von 45-64 €/tCO2, je nach Preisszenario. Die Technologie hat erwartungsgemäß weniger stark fallende Kapitalkosten, die bei Wind Onshore die größte Komponente des Preises abbildet. Aufgrund der wesentlich höheren Volllaststunden im Vergleich mit PV fällt dieser Faktor jedoch nicht so stark ins Gewicht wie bei solaren Energieträgern. Von 2020 bis 2050 sinken die Vermeidungskosten um etwa 130%

Die Arbeit zeigt die Bedeutung von Investitionsanreizen und Förderungsmechanismen als Instrument der Klimapolitik. Ohne angemessene Unterstützung ist ein wirtschaftliches Betreiben von erneuerbaren Technologien nicht möglich. Um die Zeit zu verkürzen, bis zusätzliche Förderungen gestrichen werden können, könnte ein strengeres Emissionsziel gesetzt werden oder der Überschuss an Zertifikaten im Emissionshandelssystem (ETS) reduziert werden, wie von der Europäischen Kommission angedacht. Die könnte eine Stabilisierung und Erhöhung des CO2-Preises führen, was wiederum mehr finanzielle Möglichkeiten für einen schnelleren Ausbau von erneuerbaren Energieträgern bietet. Aufgrund von Lerneffekten würde das einen rascheren Preisverfall von Wind und PV-Technologien nach sich ziehen.

Abstract

This thesis focused on the development of marginal CO2-abatement costs (MAC) of Wind Onshore, Offshore and Photovoltaics (PV) in the power sector of Germany until 2050. The paper was divided into two parts, a literature research on past studies on that topic, and the development of a model, that shows a possible trajectory of these costs until 2050 and compares to two different CO2-price scenarios.

The MATLAB model solved an optimization problem, with fossil generators coal, CCGT and OCGT being the optimization variables at a given injection of renewables. The MAC were determined by increasing this injection by a margin of 10%, while leaving demand and mix at the same level. The difference in CO2-emissions and market value of one MWh, as well as the respective levelized costs of electricity generation (LCOE) for each year, were the base for the calculation of the MAC for the years 2020, 2030 and 2050.

For Wind Onshore, these costs decrease from 150-300 €/tCO2 in 2020 to about -50 – 100 €/tCO2 in 2050. Wind Offshore develops from 200-300 €/tCO2 in 2020 to about 50-80 €/tCO2 in 2050. Photovoltaics (PV) see a projected cost curve from 150-500 €/tCO2 towards negative abatement costs -100 - -50 €/tCO2 in 2050.

Table 2: Results for MAC from 2020-2050

in €/tCO2	2020	2030	2050
Wind Onshore	148.73 – 308.91	265.20 – 107.94	-53.90 – 100.66
Wind Offshore	200.53 – 309.39	255.78 – 146.26	45.52 – 82.47
PV	200.10 – 491.68	145.22 – 394.18	-98.27 – -35.48

At the starting point of this examination in 2020 all abatement costs are well above the EU ETS´s carbon price. Therefore the current support measures are well justified and necessary to stimulate the further extension of the technologies. Without those support policies, a shift to a low-carbon power generation and a fulfilling of any emission target would be very hard to realize, as none of the RES are expected to operate completely viable any time soon. Even when solely relying on financing through the ETS, this cannot be expected before 2030, with current technological state-of-the-art and CO2-price development kept in mind.

With an optimistic projection of the carbon price, the first technology to work economically without additional support is PV, between 2030 and 2035. This could be due to the fact that PV capital costs are expected to fall by over 70% from 2010 levels according to the DIW. (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013) The great range of MAC at 2020 stems from the LCOE range by the ISE, it narrows down until 2050, as an averaged value for different PV

technologies (open space, building integrated and others) is used for the LCOE calculations.

The costs for Wind Onshore are expected to be phased out from subsidies after 2035, when the CO_2-price reaches levels of 45-64 €/tCO_2, depending on the carbon price scenario. This technology is expected to have less falling capital costs, which are the main cost driver for the LCOE and the MAC. Due to significantly higher FLHs than PV, this factor doesn´t influence results as much as those from solar power. From 2020 to 2050 the abatement costs are falling by about 130%.

The thesis shows the importance of incentives and support measures as an instrument of climate policy. Without proper financial support an economically viable operation of low-carbon technology is simply not possible. To shorten the time until these subsidies can be phased out, a more stringent CO_2-target or the reduction of the surplus of allowances, as planned by the European Commission, could be a possibility, as it could lead to higher CO_2-prices, thus more revenue of the emission trading system (ETS). This revenue in turn could be used to finance faster extension and therefore a quicker cost decline of wind or solar technologies.

Table of Content

1 Introduction

1.1 Motivation

The European Union (EU) set a number of targets and policies in the energy and climate sector for 2020 and further. The main pillars of the 2020 package are the reduction of greenhouse gas emissions (GHG emissions) by 20% compared to 1990 levels, a 20% share of renewable energy sources (RES) in the EU´s energy mix, and an improvement of energy efficieny by 20%. (Duscha, Held, & del Rio, 2016) This was stated by the European Commission (EC) in the Renewable Energy directive of 2009/28/EC,

> *„the increased use of energy from renewable sources [...] constitutes an important part of the package of measures needed to reduce greenhouse gas emissions and comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), and other further Community and international greenhouse gas emission reduction commitments beyond 2012.“*

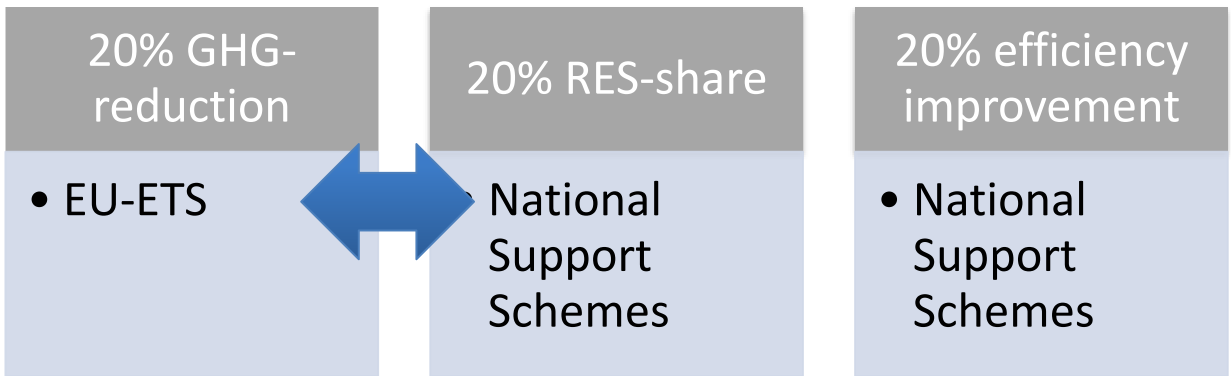


Figure 1: The EU´s 2020 targets

To achieve those targets, two main instruments are used: Firstly the deployment of RES in the energy sector needs to be promoted, using national support schemes, to fulfill the targets. Secondly, the European Emission Trading Scheme (EU-ETS) provides additional support by imposing a carbon price on emissions, thus making energy from RES more competitive. This paper takes a closer look at the interactions between those two mechanisms and their effect on CO2 abatement costs.

Though every state developed it´s own support scheme, there is one thing they all have in common: They compare to the ETS´s carbon price. (Marcantonini & Ellerman, 2013)

1.2 Core Objectives

This brings up the question, what that implied carbon price is and how it compares to the actual cost of abating a ton of CO2. Furthermore, the central question this paper is trying to answer, is, how could those abatement costs develop in the future and when would a point be reached, when the carbon abatement costs could equal the carbon price on the emission market.

This time frame is of high interest, as it marks the point, where the support costs for a technology equal the revenue of the emission market, so no additional capital is needed to further extend the technology.

To narrow down the field of the paper, only the abatement costs for onshore wind, offshore wind and photovoltaics (PV) in Germany are examined.

When looking at a marginal abatement cost curve (MAC-curve), the scope of this thesis can be explained further:

While efficiency measures or improvements on current technologies are sorted in an ascending order by costs, the implementation of renewable energy is set to a value of nearly zero through policy measures and support schemes. With the emission reduction target for the time period staying at a constant level, this shifts the MAC-curve to the right, making a less expensive technology improvement or efficiency measure the one with the highest investment.

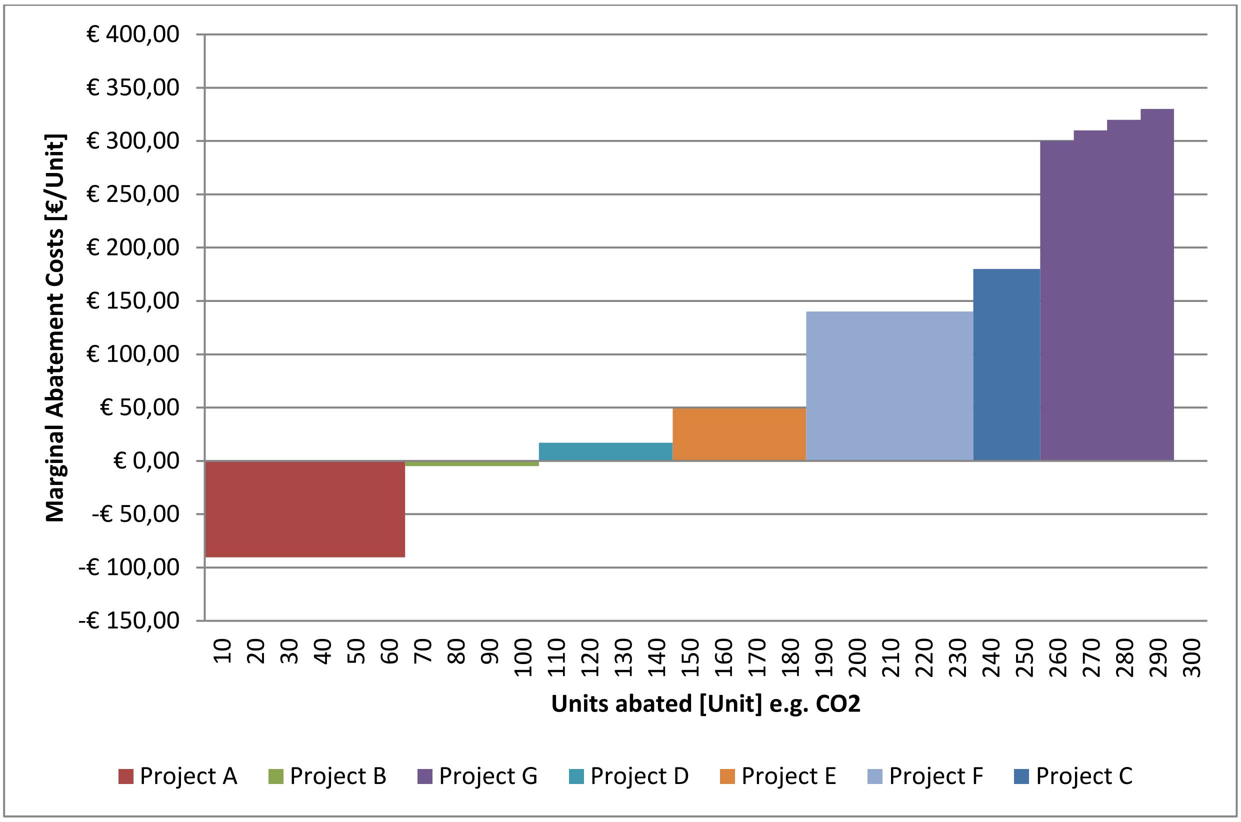


Figure 2: Marginal Abatement Cost Curve

Project A to F can be seen as efficiency measures, Project G is the collective of all RES deployed. If the abatement target is 270 Units, the highest investment would cost about 300€ per Unit abated. With the implementation of support schemes and policy measures for RES, which sets Project G´s costs to zero, this shifts to 140€ per Unit abated.

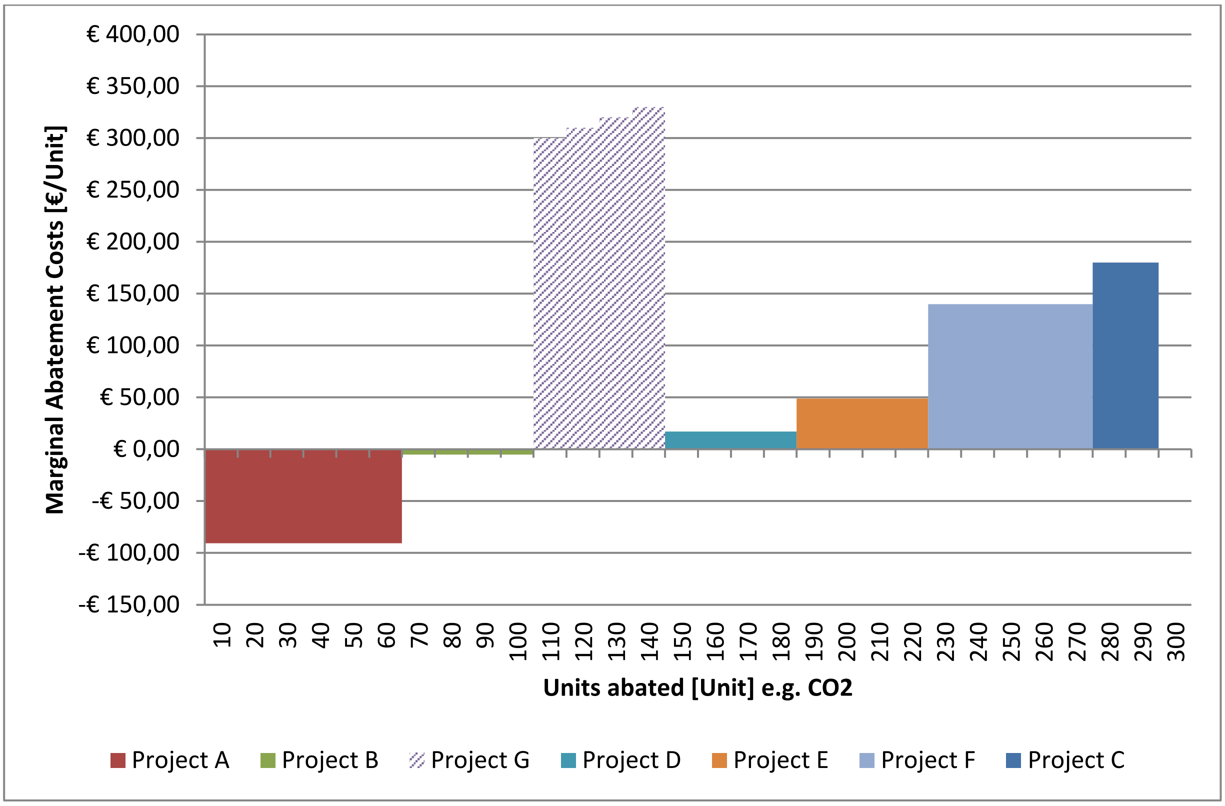


Figure 3: MAC curve with support scheme for RES

Together with the expenses for the support schemes, like premium payments, the total system costs are higher. Due to other positive effects on the economy like innovation, jobs, growth or environmental effects like lower fine particulates in the atmosphere, those higher costs are taken into account.

Through learning effects and further expansion of RES, the abatement costs are expected to sink over time, resulting in lower expenses for the support schemes for newly built capacity.

1.3 Structure

This thesis will be divided into two main parts: Firstly a literature review and analysis of existing papers on the development marginal abatement costs, and secondly the calculation of the projected development of carbon abatement costs for PV, Wind Onshore and Wind Offshore.

The second part is conducted by using a MATLAB model developed by the Energy Economics Group of the Technical University Vienna (EEG). With adaptions made by me, it uses a projected electricity mix for 2020, 2030 and 2050 to calculate the amount of CO2 abated.

Together with the projected costs of the technology until 2050 a possible development of the abatement costs over time can be constructed.

This data can then be compared to carbon certificate price outlooks from different sources like the „Price Induced Market Equilibrium System Energy Model“ (PRIMES), to analyze if and when the technology is able to become competitive without additional support mechanisms.

A more in-depth explanation of the model, formulas and workflow can be found in Chapter 3.

1.4 Major references

The projected costs of the technology were taken from an 2014 ISE Fraunhofer report by Held et al. and a 2013 DIW documentation by Schroeder et al.. Data for the carbon certificates until 2050 was sourced from the EU-financed PRIMES model.

These sources will be examined in detail in a future chapter of this thesis.

Major sources for literature were Macarontini et al. and Criqui et. al., who published comprehensive papers on marginal abatement costs.

2 General

This chapter will give a short overview over the existing system, explain the EU Emission Trading System (EU-ETS), define marginal CO_2 Abatement Costs and give a short introduction to the topic of technological learning.

2.1 The EU Emission Trading System (EU-ETS)

As a cap-and-trade system the EU Emission Trading System (EU-ETS) defines allowed CO_2 emissions for around 50% of the EU´s total emission volume. Those allowances can be traded by the participants, so the most cost-efficient way to reduce emissions can be realised.

The ETS was introduced in 2005 and is, with a coverage of 11.000 power and industrial plants in 31 countries, the world´s largest emission trading system. It´s main goal is to reduce the EU´s greenhouse gas emissions (GHG emissions) to fulfill the climate change goals set in the Kyoto Protocol of 1997. (European Commission, 2015) (Marcantonini & Ellerman, 2013)

The most important aspect of the ETS is the capping of overall GHG emissions for all players in the system. This is done by creating allowances for emitting GHG emissions, which equal the global warming potential of 1 tonne of CO_2 equivalent. The overall cap of the system sets the total number of allowances in the whole system. Starting in 2013 with phase 3 of the EU-ETS, this cap is reduced every year by 1,74%, so all the participants of the system have a reduced amount of allowances every year.

Figure 4: Phases of the EU-ETS (European Commission, 2015)

Phase 1 was a development phases to establish a carbon price, a trading system and all the infrastructure necessary to monitor emissions from participants of the system. Phase 2 lowered the cap for the first time, as the participating countries had their first Kyoto Protocol targets to meet. Due to the financial crisis in 2008 the reductions of emissions were higher than expected, leading to a surplus of allowances, that reduced the CO2-allowance price significantly.

Phase 3 implemented the mechanism of “back-loading” to reduce that surplus and to increase the carbon price and the incentives to reduce emissions. This “back-loading” postpones the auction of 900 million allowances until 2019/2020 and can be seen as a short term measure to stabilize the allowance price. For the long-term another mechanism will be implemented in early 2019, the market stability reserve (MSR). Instead of auctioning the back-loaded allowances, they will be transferred to this reserve, thus controlling the amount of allowances on the market, that are available for auctioning.

Phase 4 will increase the capacity of the MSR significantly to ensure further stability of the allowance markets. Also, the cap will be reduced by 2.2%, instead of 1,74% every year in phase 3. With those measures the sectors participating in the EU ETS seek to reduce their emissions by 43%, when compared to 2005, to fulfill the general GHG reduction target of the EU.

As mentioned above, all the participants of the ETS need to buy their allowances through auctions, except certain industries, that are prone to move their production to countries with less stringent emission regulation. This shift is also known as “carbon-leakage”. Those participants receive their allowances for free.

Every business in the ETS has to return one allowance for each tonne of CO2 emitted during the year, if not, additional allowances have to be purchased either through auctions, or from other participants, whose measures to reduce emissions created a surplus of allowances. If those regulations aren´t met, a penalty of 100€/t CO2 is imposed, to make sure all participants comply and the environmental benefits of the system are ensured.

The EU ETS includes all member states of the EU, as well as Norway, Iceland and Liechtenstein, covering the whole European Economic Area (EEA). It covers the industry sectors with the highest GHG intensity, first and foremost the power sector. It expaned to the aviation sector, and with phase 3 also includes the aluminium, carbon capture and storage (CCS), petrochemical and chemical sector. Next to CO2 emissions, the EU ETS also covers specific emissions from the chemical and aluminium industry. (European Commission, 2015)

The carbon price is driven by supply and demand of the market, which makes the number of allowances on the market a key figure for a stable price for European

Union Allowances (EUAs). While the demand on the market is increased through the linear reduction of 1.74% per year (2.2% respectively after 2021), the supply can be affected by the backloading or the MSR. Another factor that comes into play is the reduction of eligible companies for free allocation of allowances during phase 4, which is also expected to increase the EUA price. (Twidale, 2018)

2.2 Carbon Abatement Costs

The ETS´s revenue is being used to support investment in low carbon and renewable energy technologies, for example wind power or photovoltaics (PV), as well as energy efficiency measures. To make the cost of those technologies comparable to the allowance price the term of “Carbon Abatement Costs” is introduced.

Per definition, the cost of reducing CO2 emissions by one unit (Gt, t) through the deployment of a specific technology or measurement, when comparing to a business as usual scenario, is called carbon marginal abatement cost (MAC). (Beer, Corradini, Gobmaier, & Köll, 2009)

$$MAC_{CO2} = \frac{C_{Measure} - C_{Reference}}{E_{Reference} - E_{Measure}} = \frac{\Delta C}{\Delta E_{specific}} \tag{1}$$

$C_{Measure}$	$specific\ costs\ of\ measure\ in\ €/MWh$
$C_{Reference}$	$specific\ costs\ of\ reference\ in\ €/MWh$
$E_{Reference}$	$specific\ emissions\ of\ reference\ in\ tCO2/MWh$
$E_{Measure}$	$specific\ emissions\ of\ measure\ in\ tCO2/MWh$

Following the definition, this formula is only applicable, if the difference of the specific emissions is negative. Therefore negative abatememt costs are only possible, when there is more money saved, than being invested. Therefore, when leaving any support policies aside, measurements with negative abatement costs are economically viable.

According to Criqui et al., the MACs can vary due to different structural factors in different countries:

- The level of energy prices at the reference point – the carbon value is expected to have a relatively large effect in countries with low energy taxation and prices
- The structure of energy supply – cheap measures can be implemented in countries with high carbon energy sources like coal, through subsitution with e.g. natural gas
- Potential for renewable energy systems (RES) or industrial capacity for nuclear energy

For further explanation, we assume two countries with different MACs for a specific measurement, seeking to reduce their emissions. Between Country A and B exists a market to exchange emission permits. Country A wants to reduce it´s own effort by not meeting it´s own target. Therefore it needs to buy permits from country B to comply with the target. Country B reduced it´s emissions beyond it´s own target, up to a point, where its MACs were equal to the market´s MAC.

The conclusion of this scenario is, that „*supply and demand are balanced, if the price is equal to the marginal costs on the market*." (Criqui, Mima, & Viguier, 1999) This makes the MAC the ideal orientation point for the price of carbon permits.

Both countries benefit from the trade: Country A fulfills it´s targets by obtaining permits for a lower price than it´s own measurements. Country B sells those permits and generates revenue, that it can use for further reductions.

2.3 Technological learning

To determine the development of carbon abatement costs it is crucial to predict the costs of the specific technology or measurement in the future.

A common tool for this is the learning curve, sometimes also referred to as experience curve. (Li, Zhang, Gao, & Jin, 2012) According to Neij, the term "learning curve" is used to describe cost reductions of a standardised product on company level while "experience curves" describe the cost reductions of a non-standardised product on a national or global level (Neij, 1999)

This tool can be used to evaluate public policies established for technology support, to develop long-term energy and GHG reduction strategies or to determine the speed of improvement of certain technologies. (Nakata, Sato, Kusunoki, & Furubayashi, 2011) They can also be used to built scenarios for the total technological development and capacity, as done by Held et al..

The time scope for the use of learning curves ranges from a year up to models that cover up to 100 years for certain global models. The problem with the use of technological learning on a global scale is the high diversity in local policies and geographical differences. Therefore the use of national results, as done by many global models, leads to uncertainties for the final cost reduction curves. (Junginger, Faaij, & Turkenburg, 2005)

Empirically the cost of a technology decreases at a fixed rate with every doubling of the installed capacity. The learning curve describes this relation mathematically. (Junginger, et al., 2006)

$$C_n = C_0 \cdot C_{Cum}^b \tag{2}$$

C_n	$cost\ for\ the\ last\ unit\ produced$
C_0	$cost\ for\ the\ first\ unit\ produced$
C_{Cum}	$cummulative\ volume\ produced$
b	$index\ of\ experience$

The experience index is calculated according to (3)

$$2^b = PR \tag{3}$$

PR	$progress\ rate$

This progress rate is connected with the learning rate (LR) through (4).

$$PR = 1 - LR \tag{4}$$

LR	$learning\ rate$

This learning rate represents the cost reduction per doubling of installed capacity or cummulative volume produced. This means, that with a learning rate of, for example, 0.15, the costs of this specific technology is reduced by 15% when the capacity is doubled once.

Formula (1) shows that the cost development is depending not only on cummulative production, but also highly influenced by the LR. Especially when looking at the scope of this thesis, which uses cost progressions of Wind and PV, it is important to understand, how those forecasts were derived. (Li, Zhang, Gao, & Jin, 2012)

An example of how such a experience curve looks like is shown in Figure 5. Since a double-logarithmic diagram is used very commonly throughout the literature, the experience curve becomes a straight line. This makes it easy to identify the progress ratio and experience effect, which is often used to compare different curves. Those two factors are the same in every area of the curve.

As a result of the double-logaritmic diagram, this means, that a young technology with low installed capacity will learn much faster than a more mature one. An increase of 1 to 2 MW would mean a decrease of the price by 24%, according to Figure 5, while the step from 1 GW to 2 GW is a much larger one, that takes more time and financial effort. Therefore, when looking at broadly used technologies, the price reduction effect per additional MW that is modeled in the experience curve, won´t be significant. (IEA, 2000)

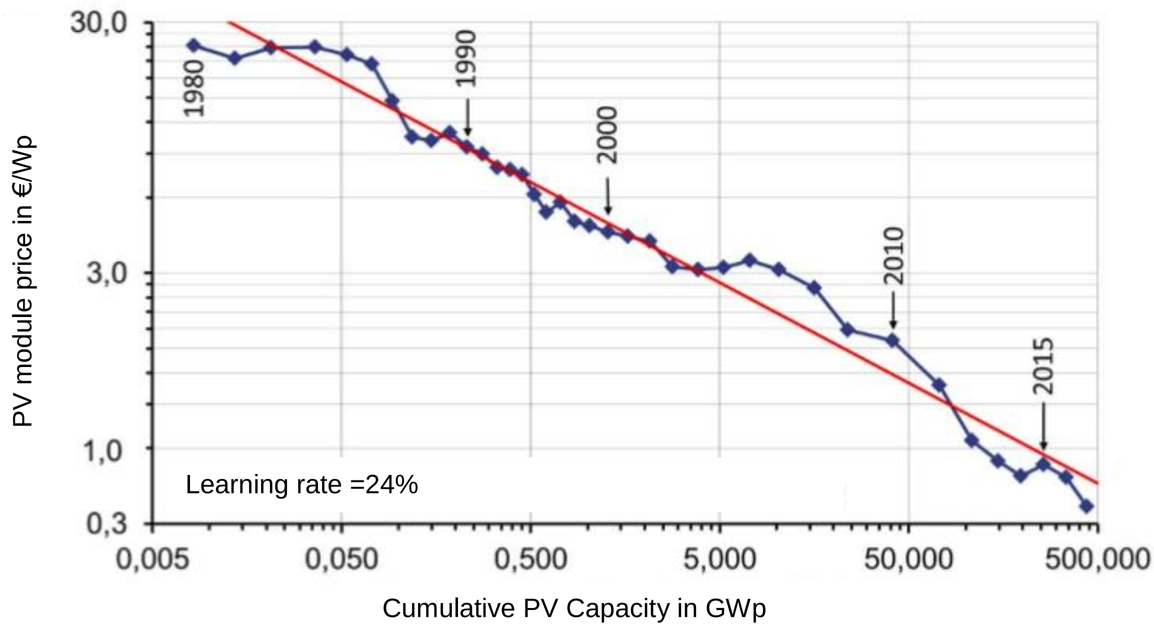


Figure 5: Experience Curve for PV from 1980 -2015 (Fraunhofer ISE, 2015)

Even through significant improvements of particular components of a technology, for example improved maintenance of wind power plants, those price components still are a part of a mostly mature technology, and will therefore be less significant than a completely new technology introduced to the market.

When we look at wind power this effect can be explaned quite easily: the component of the turbine sees a relatively low learning rate of 4%, mostly through increasing size. (Figure 6) (Neij, 1999) The learning rate of wind power in total is significantly larger, which means that the total experience curve only shows, how much is learned in other fields or components like power management, site decisions or improved maintenance, which are all much newer fields or technologies than the turbines themself. (IEA, 2000)

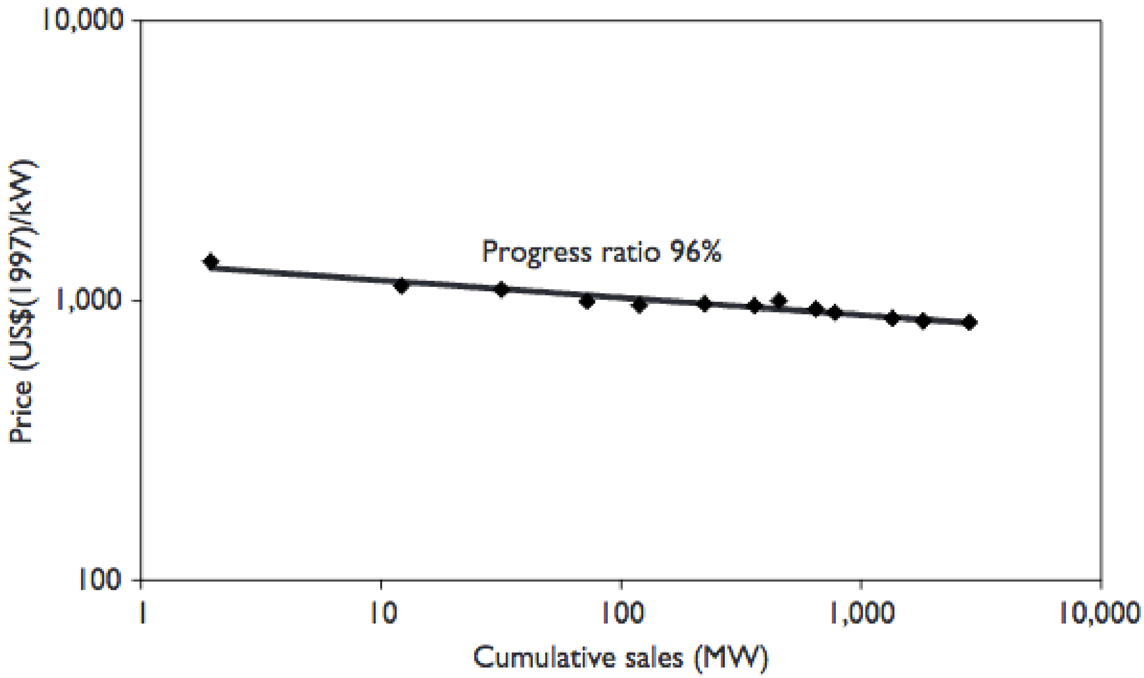


Figure 6: Experience curve of Danish wind turbines 1982-1997 (IEA, 2000)

The cost reductions can be caused by different factors: (Abell & Hammond, 1979) (Grübler, 1998)

- The costs can be reduced by improved efficiency, improvements and further specializations caused by a learning-by-doing or learning-by-using
- Innovations through research and development
- Better transfer of knowledge between research institutes, industry makers and other participants
- Establishment of a standardised production to increase production rate
- Adjusting the design or size of the product to reduce costs

Most of the time a combination of those factors affects the price, weighting differently over time. For example, innovations through research and development can have a very high impact on the costs during the early stages of the product development, while a standardised production is especially important, when the product is already well established and mass production could lower the price significantly. (Junginger, Faaij, & Turkenburg, 2005)

The concept of the experience curve is used to describe the development of a specific technology in the future, showing that more installed capacity means a lower production or investment price. It does not show, when the technology will reach a certain price level. That time is specified by the rate of deployment, which is highly influenced through policy. In case of Germany, the driving policies for Wind and PV are the EU´s targets for RES and GHG emissions. More ambitious deployment of those technologies would also lead to a faster decrease of the electricity cost.

The investments needed to move down the experience curve are called learning investments and are primarily provided through market mechanisms. The main goal of those investments is the overcoming of cost barriers and making the technology commercial. (IEA, 2000)

3 Methodology

This chapter will explain, how the resulting data for MAC was derived and how existing literature about carbon abatement was chosen. Main formulas for the calculation and the procedure for the used MATLAB model and the model itself are also described.

3.1 Literatur research

The first step of this thesis was a literatur research on studies about the development of CO2 abatement costs in the past, to find out if any comparable results are already available. Research sources were the library of the Technical University of Vienna, as well as the use of online resources for scientific papers.

It is important to note, that only studies, that examined wind power and PV were taken into this literature research and only explicit calculations on carbon abatement costs were analyzed.

3.2 Model & Model description

This chapter described the used MATLAB model and how it is working. It also contains the main formulas used in the calculations of the MAC and the procedure used to determine the necessary factors for these calculations.

3.2.1 MATLAB Model

The base for the used MATLAB model is a dispatch model, that was used during the lecture “Selected Topics of Energy Economics” by Andreas Fleischhacker at the TU Vienna. It´s main goal was to find out an optimal capacity of conventional power generators for a given demand on a specific day. Renewable energy systems (RES) are considered must-run technologies. This model was converted to an investment model. Results were the optimal capacity and the optimal dispatch for a given demand.

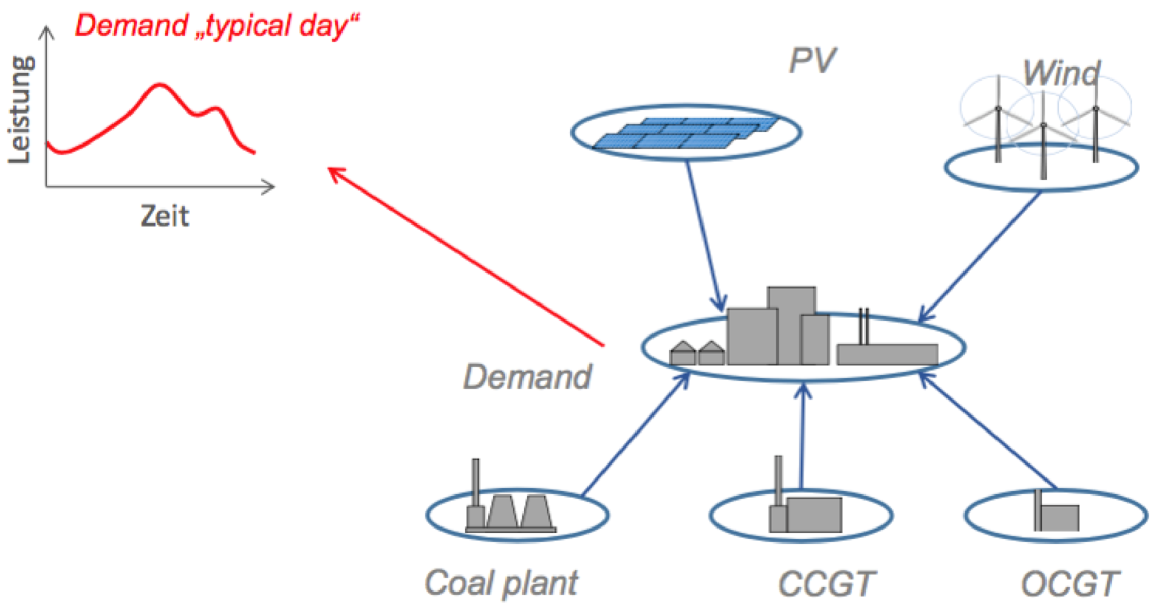


Figure 7: Dispatch model from lecture as a base for the used model (Fleischhacker, 2016)

Also, the shadow price of the demand was determined. It represents the marginal additional costs of a demand increase of one MWh, which can be interpreted as the price of one MWh in a specific hour. (Fleischhacker, 2016)

For this thesis that model was adapted on several point:

- the time scope was changed from one day (24 hours) to 12 weeks (2016 hours) to have a representative time frame of a year.
- an additional renewable energy source was added through the splitting of the renewable source of “Wind” in “WindOnshore” and “WindOffshore”.
- CO2 emissions of the used conventional power plants were calculated and summed up in the results
- the shadow price of CO2 was also calculated
- a CO2 budget was integrated to ensure compliance that emission limits

There are various input parameters to the model:

- the demand profile for the 12 week time period for Germany
- the feed-in profile of the examined renewable energy technologies, “WindOnshore”, “WindOffshore” and “PV”
- efficiency factors for the conventional power plants, “Coal”, “Combined-Cycle-Gas-Turbine (CCGT)” and “Open-Cycle-Gas-Turbine (OCGT)”
- fuel costs for coal and gas
- emission factors for the conventional technologies

- cost determining factors, namely investment costs “CInv”, fixed operational and maintenance costs “OPEX”, variable operational and maintenance costs “VarOPEX”, lifetime of the facility and a given discount rate
- CO_2 costs from two different scenarios, “Reference-16” and “EUCO-27”. This data is described in detail in the chapter “Used data”.
- a CO_2-Budget

As mentioned above, the model is trying to solve an optimization problem. The optimization variables are, as written in the code, the conventional power plant capacity “pConventional”, the wind capacities “pWindOn” and “pWindOff” and the photovoltaic capacity “pPV”.

The problem is solved by using the parser “YALMIP”, which is a linear matrix inequality (LMI) parser. One great advantage of this LMI approach is, that it can translate the LMI problem into an optimization problem, that can be solved by already developed numerical algorithms. (Shenggyuan & Lam, 2008) A more detailed insight into the topic of LMI problems is not a part of this thesis.

In this particular case, the solver used to handle the problem is called “Gurobi”. The Gurobi Solver is an optimization solver for linear, quadratic and mixed-integer problems, that is currently being used by a great number of companies throughout different industry sectors.

To summarize, the results of one iteration of the MATLAB model include:

- necessary capacity of conventional power plants to cover the demand
- the market value of one MWh for every single hour and an average value for the whole time period
- the specific and total CO_2 emissions of the conventional power plants

3.2.2 Formulas

The results of the MATLAB model do not yet represent the marginal abatement costs of Wind Onshore, Offshore and PV. Several steps and iterations must be conducted to achieve this target and every step must be done for each technology and each time point, the year 2020, 2030 and 2050. This way a trend for the development of the abatement costs can be calculated.

Firstly, the market value (MV) needs to be set in a relation with the costs that electricity generators have for producing one MWh. The difference of those two has to be covered by the support costs (see Formula (5)), which usually derive from public sources.

$$LCOE - MV = C_{Support} \tag{5}$$

MV	$market\ value, according\ to\ MATLAB\ model\ in\ €/MWh$
$LCOE$	$levelized\ cost\ of\ electricity\ generation\ in\ €/MWh$
$C_{Support}$	$cost\ of\ support\ measures\ in\ €/MWh$

The cost of support measures is then used to calculate the marginal carbon abatement costs. It considers market development and individual situations like fluctuating prices, as well as the learning effects of the respective technologies (Wind & PV).

The market value is an average of all the marginal prices from the MATLAB optimization model.

For the LCOE for the years 2020 and 2030 data from a 2014 LCOE estimating report by the Fraunhofer Institute (Held, et al., 2014) was used. For the year 2050 separate calculations based on a cost outlook by the DIW (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013) are being used.

The LCOE of 2050 for Wind Onshore, Offshore and PV were calculated according to Formula (6).

$$LCOE = \frac{\alpha \cdot (C_{Cap} + C_{O\&M}) + C_{Var}}{FLH} \tag{6}$$

α	$annuity\ factor\ in\ 1/a$
C_{Cap}	$initial\ capital\ costs\ in\ €/MW$
$C_{O\&M}$	$costs\ for\ operation\ and\ maintenance$
C_{Var}	$variable\ costs\ per\ year\ in\ €/MW \cdot a$
FLH	$full\ load\ hours\ in\ h/a$

Capital costs, costs for operation and maintenance (O&M) and variable costs were taken from the cost outlook of the DIW, while the full load hours were taken from the Fraunhofer paper.

With these formulas the necessary support cost for wind onshore, wind offshore and PV for the years 2020, 2030 and 2050 can be calculated.

Secondly, to calculate the abatement costs over time, the following formula, adapted from formula (1), is being used.

$$MAC_n = \frac{C_{Support}}{E_{Reference} - E_{Measure}} \tag{7}$$

MAC	$marginal\ abatement\ costs\ in\ €/t_{CO2}$
$E_{Reference}$	$emissions\ of\ the\ reference\ scenario\ in\ t_{CO2}/MWh$
$E_{Measure}$	$emissions\ of\ a\ scenario\ in\ t_{CO2}/MWh$
$C_{Support}$	$cost\ of\ support\ measures\ in\ €/MWh$

The reference scenario emissions were taken directly from the MATLAB model results for the reference data input. This means that the projected feed-in of renewable energy sources was left untouched, and solely a first optimization run was conducted. More on the exact procedure is explained in the next chapter.

The scenarios involved an additional extension of 10% of the capacity for the respective technology in the respective year.

The difference between these two emissions are the amount of CO2 abated per additional MWh of the renewable energy source generated.

Together, with formula (7), the abatement costs are calculated, the results being a range of values for each moment examined, due to the fact, that the FLHs vary for each location of the powerplant.

3.2.3 Procedure

Step 1:

The first step is the correct input of all the variables described in the previous chapter. This involves:

- cross-referencing the correct demand profile and feed-in of Wind and PV
- the correct CO2-price and fuel prices for coal and gas for the examined moment of time
- the right cost data for conventional technology

It is important to point out, that the Excel data, as mentioned before, a time row of Germany´s electricity production and demand for 2016 hours, has to be adjusted properly by subtracting fossil energy generators and other generators like nuclear, biomass, pump storage, import/export power, run of river and other renewable energy sources, which part of the model.

The input is done from line 1 to line 107 in the MATLAB model.

Step 2:

The first run is used to calculate the optimal mix of conventionals and the emissions for the base scenario, with all the renewable energy feed-in at their standard level.

Step 3:

For the second run some other changes to the base model need to be made:

- the capacity mix of the first run is to be used instead of setting line 37 to zero as in the base scenario
- the CO2-price (line 63-68) needs to be set to zero
- the newly built capacity needs to be set to zero (line 138)
- the RES technology examined needs to be extended by 10% in the Excel data sheet, the reference in the MATLAB model has to be updated

The CO2-price is set to zero to determine a market price not influenced by the price of the emission allowances.

To determine a difference in emissions between the two scenarios, there is no additional capacity to be added, therefore this line is set to zero and the capacity is set to the base scenario values.

Step 4:

The second run gives out results for the market value without the influence of CO2-prices. It gives out the value of CO2-emissions for the 10%-extension scenario of one of the renewable technologies examined.

Step 5:

With the formulas (5), (6), (7) and the results available from the MATLAB iterations, the marginal abatement costs can be calculated.

Step 1-5 have to be conducted for every examined moment of time (2020, 2030, 2050) and every renewable technology examined (Wind Onshore, Wind Offshore, PV).

This data is then presented in diagrams that show the range of marginal abatement costs of the respective technology in comparison with two CO2-allowance scenarios until the year 2050. As mentioned before, the range is a result of different FLHs for every power plant location.

4 Past studies on CO2 abatement cost

Numerous studies on the development of CO2 abatement costs in different countries, for different sectors and under different circumstances can be found throughout the libraries. Also when looking at Feed-In tariffs, a number of studies can be found. However, when it comes to Germany, and more specific, the abatement costs of RES like Wind or PV, the number is quite limited.

4.1 DENA-Study

One of the most substantial ones in this area was conducted by the German Energy Agency DENA in 2005, and examined the CO2-abatement of wind power while also looking at the impact of the local FITs (feed-in tarifs).

With the years 2007, 2010 and 2015 as data points, the total system cost and the CO2 emissions were examined through two scenarios: the first one with a constant wind power capacity as of 2003, the second one with a large extension as a result of the FIT. The CO2-prices used range from 5-10 €/tCO2, the CO2-abamement costs in the second scenario develop from 168 €/tCO2 in 2003 to €40,6 €/tCO2 in 2015. The results also depend on the asumptions made for fuel and carbon prices. Compared to other abatement possibilities, like power plant modernizations, new built capacity or efficiency improvements on the consumer side, these costs are relatively high (for the base 2007). The costs are calculate as the relation of the costs for the wind extension and the abated CO2-emissions for each scenario. Over time they decrease significantly, as the specific costs of the wind energy injection sink, due to lower FITs and higher savings in the conventional power plant mix.

When looking at the scenarios, two effects can be observed: firstly, the increase of CO2 abatement when coal power production is reduced. Secondly, a higher fuel or CO2-price leads to higher cost savings in the conventional mix. The first effect is visible in the base scenario, the second in the base + CO2 scenario. Both of them can be seen in the alternative scenario, leading to substantially lower abatement costs in 2015. (Jansen, Molly, & Neddermann, 2005)

The absolute amount of abated CO2 is shown in Table 3.

Table 3: CO2-abatement of an extension of wind power (on a 2003 base) (Jansen, Molly, & Neddermann, 2005)

		2007	2010	2015
Base Scenario	CO2-Abatement in Mt	8.0	28.3	39.5
	CO2-Abatement in kg/MWh additional windpower	605	817	738
	CO2-abatement costs in €/tCO2	104.7	73.4	58.9
Base Scenario + CO2	CO2-Abatement in Mt	8.8	20.8	27.2
	CO2-Abatement in kg/MWh additional windpower	667	600	508
	CO2-abatement costs in €/tCO2	95.1	86.8	76.6
Alternative Scenario	CO2-Abatement in Mt	5.1	26.3	39.4
	CO2-Abatement in kg/MWh additional windpower	387	758	735
	CO2-abatement costs in €/tCO2	168	56.6	40.6

The data was adjusted to reflect the variations of power import and export with and without the extension of wind energy. When looking at the abatement costs for the base scenario + CO2, and the alternative scenario, it has to be noted, that the internalisation of a part of the extern cost factors on the base of the emission allowance price, leading to higher variable costs of the conventional plants, already contribute to higher cost abatement per each additional MWh of wind energy.

Depending on the year and scenario, the abatement of CO2 per MWh ranges from 400-800 kgCO2/MWh. These high specific carbon savings can be derived from two factors: Firstly, only conventional, fossil generators are substituted. Secondly, a higher generation of wind power plants favors power plants with lower capital costs, as the preferred feed-in of wind power lowers the FLHs of the conventional plants on average. This makes CCGT and OCGT power plants more competitive and lowers specific emissions in the conventional part of the generation mix.

4.2 Meta-Analysis on CO2-abatement by Kuik & Brander

A greater overlook was given by Kuik & Brander, as their paper summarized information from 26 models in a meta-analysis until the year 2050. Unfortunately a deeper look into the exact development and impact of wind power and PV CO2-abatement cost development was not possible. Nevertheless, the results gave important insights on how MACs are influenced. Naturally they are strongly dependend on the emission target.

For the results those targets were converted to ppmv CO2 concentration measures, between 350 and 550 ppmv CO2. Different stabilization targets were classified by Fisher and Nakicenovic in 2007, giving a relation between the global mean temperature increase and CO2-concentrations in the atmosphere. Most of the studies used in this meta-analysis used category III and IV targets.

Table 4: Temperature stabilization targets vs. alternative metrics (Fisher, et al., 2007)

	additional radiative forcing	CO2-concentration	CO2-equivalent concentration	mean temperature increase
Category	W/m2	Ppm	ppm	degree Celsius
I	2.5-3.0	350-400	445-490	2.1
II	3.0-3.5	400-440	490-535	
III	3.5-4.0	440-485	535-590	2.9
IV	4.0-5.0	485-570	590-710	3.6
V	5.0-6.0	570-660	710-855	4.3
VI	6.0-7.5	660-790	855-1130	5.5

The results of the study are shown in Table 5. The difference between the full database and the restricted database is due to one study that was excluded, as the baseline emissions contained incomplete information and resulted in very high MAC of 449.3 €/tCO2. (Kuik, Brander, & Tol, 2008)

Table 5: Statistical results of the meta-analysis for 26 models (Kuik, Brander, & Tol, 2008)

	2025		2050	
	Full database	Restricted database	Full database	Restricted database
Mean	23.8	23.8	63.0	55.8
Median	16.2	16.2	34.6	32.2
Maximum	119.9	119.9	449.3	209.4
Minimum	0.0	0.4	1.4	1.4
St.dev.	26.7	27.9	72.5	52.9
N	62	47	62	49

The examined studies used different assumptions on economic growth, industry structure and technological developments, which led to a great range of baseline emissions and furthermore different relations between the emission targets and the abatement costs. Figure 8 shows these relations, together with a 95% uncertainty of the prediction.

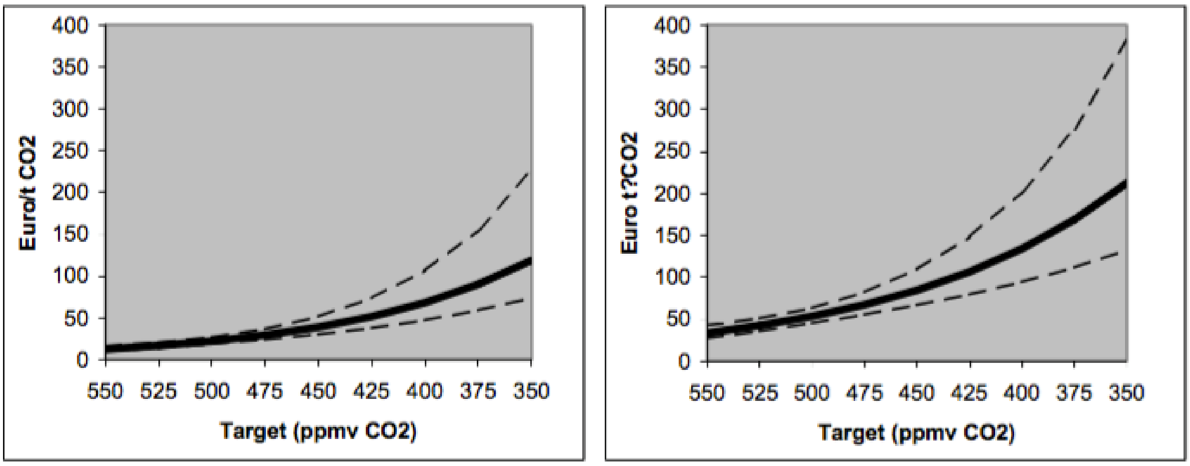


Figure 8: Target vs. MAC (Left 2025, right 2050) (Kuik, Brander, & Tol, 2008)

Since most of the studies in this meta-analysis show a target of category III or IV, this range has a relatively low range of abatement costs. When looking at the lowest emission target of 350 ppmv, which represents almost the EU´s target of 2 degrees Celsius (von Asselt & Biermann, 2007), the range spans from € 74 and € 227 in 2025 and between € 132 and € 381 in 2050. (Kuik, Brander, & Tol, 2008)

Since the MAC projection can be seen as an ideal carbon emission allowance price in a idealized global ETS, the results of the meta-analysis were compared with two other studies, one looking at the United Kingdom´s MAC (Watkiss, 2005), with a targeted 60% emission reduction, and the other one on a EU level, with the policy targets for the year 2020. (Elzen, Lucas, & Gijsen, 2007) According to Kuik et. al. those targets lie within the range of result of the meta-analysis, as can be seen in Table 6.

Table 6: Comparison of national and EU MAC with study results (Kuik, Brander, & Tol, 2008)

	2020 (in €/tCO2)	2050 (in €/tCO2)
UK	15-60	142-193
EU-27	23-93	
MAC of study (350-550 ppv)	13-119 (for 2025)	34-212

The results show a idealized global MAC, which assumes a optimal and rational global policy, so under other circumstances those costs might as well be much higher. (Kuik, Brander, & Tol, 2008)

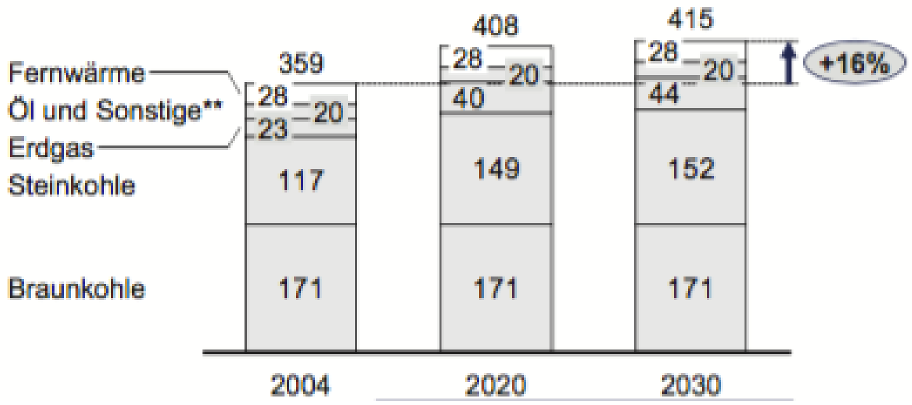
4.3 McKinsey-Study

A McKinsey study from the year 2007 gave an outlook on how the abatement costs of renewables could develop until the year 2030 in Germany.

This was done, as a first step, through the modelling of the future development of GHG emissions, based on two principles:

- a given gross domestic product (GDP) growth of 1.6% per year, that corresponds to a higher production rate throughout the industry and the connected increase in power demand
- all newly set measures are on an average and actual state-of-art level

Political targets and self-imposed regulations of particular industry sectors were left out of the picture, also the German support scheme for the extension of renewable energies, the “Erneuerbare Energie Gesetz (EEG)” was left out and only projects already being built or planned were considered. The most significant circumstance for the power sector was the nuclear phase-out until 2022, which is, of course, considered. Together with a number of technology specific assumptions, the projected emissions until 2030 were calculated.



Translation:

“Fernwärme” – district heating
“Öl” – oil based generation
“Steinkohle” – coal
“Braunkohle” – brown coal

Figure 9: Projected GHG-emissions until 2030 in Mt CO2 (Vahlenkamp, 2007)

The projected GHG emissions are in part caused by economic growth, but largely due to a increase in CO2-intensity of power generation. This is the result of the nuclear phase-out, leading to an extension of conventional generators.

Table 7: CO2-Intensity and power generation

	2004	2020	2030
Generation in TWh	616	636	661
CO2-intensity in tCO2/MWh	0.57	0.64	0.62

From an economical point of view and without considering CO2-prices and support policies as done in this first calculation, the missing capacity of nuclear must be replaced by new gas and coal generators, as RES would not be competitive without governmental support. (Vahlenkamp, 2007)

This data is the base for the evaluation of the abatement cost. The study looked at several measures to abate emissions and compared their costs to the reference technologies from the previous calculations.

The potential was determined in three steps:

- Step 1: greatest technically possible potential under consideration of limitations (e.g. resources)
- Step 2: market penetration rate, lowering the potential, due to non-economic preferences

- Step 3: interconnections between abatement technologies. The measurements abating emissions were priorized over the ones lowering CO_2, and already established technologies were priorized over new or future technologies.

For the calculation of the abatement costs, the cost difference between the measurement and the reference technology was evaluated completely. For every technology a specific learning rate was used, that led to a cost reduction between 2020 and 2030.

As for wind, Onshore and Offshore, the study sees a increase to 65 TWh production in 2020, with a potential of 22 Mt CO_2, making the generation from wind power plants one of the most important measurements for carbon abatement.

Table 8: MAC for Wind Onshore and Offshore in 2020 (Vahlenkamp, 2007)

	LCOE (in €/MWh)	Projected Generation in TWh	Potential (in $MtCO_2$)	MAC (in €/tCO_2)
Onshore	67	48	11	58
Offshore	73	17	11	104

Onshore wind power generation is expected to see an increase due to the exploitation of new locations and the repowering of old power plants, which increases their capacity.

Due to falling investment costs, the LCOE of Offshore wind are expected to reach similar levels in 2020. As those calculations do not consider the costs for the grid connection of the offshore power plants, which the generator does not have to finance, the MAC are significantly higher in comparison to Onshore.

PV is not expected to play a large role in abating emissions, with only 2 $MtCO_2$, representing only 2% of the potential of RES. The abatement costs are expected at around 200€/tCO_2.

Until 2030 the study sees CO_2-abatement costs decrease for wind onshore from 58 €/tCO_2 to 53 €/tCO_2. Wind Offshore goes from 104 €/tCO_2 to 85 €/tCO_2, PV power plants from 153 €/tCO_2 to 123 €/tCO_2 abated.

Table 9: MAC from 2020-2030 (Vahlenkamp, 2007)

	2020	2030
Wind Onshore	58	53
Wind Offshore	104	85
PV	153	123

According to the study the biggest contribution to the abatement of greenhouse gases comes from the shift to renewables. The biggest part of the CO2 abatement potential of 61 MtCO2 in 2030 has the power production from wind (On- and Offshore) and biomass. The potential of PV extension has a relatively low economically viable abatement potential, due to the high substitiution of the technology. Other abatement measurements like Carbon Capture and Storage technology (CCS) or biomass weren´t examined in detail in this literature review.

The study concludes by pointing out the importance of wind power for the reduction of GHG emissions, as well as the implementation of CCS. It also looked at a possible scenario, where the nuclear phase-out of Germany would be delayed. In this particular scenario, that won´t be subject to further discussion in this paper, the abatement potential was significantly higher, and the costs 4,5 billion €/year lower. (Vahlenkamp, 2007)

5 Used Data

This chapter describes the data that was implemented into the model and the further calculations. It also shortly explains how this data was calculated, according to the studies used.

5.1 Data for demand and power generation

The Excel data, used for the MATLAB model, for fossil generation, load and renewable energy generation was provided by the Energy Economics Group (EEG) of the Technical University of Vienna (TU Vienna).

This data is a time row for Germany´s power sector until 2050 and contains load, demand, electricity price, the generation profile of fossil and renewable generators, import/export, as well as transmission losses. For simplification reasons several generators were subtracted from the demand. These generators were all renewables other than Wind Onshore, Offshore and PV, pump storage and run of river power, nuclear power, storages in general and import/export numbers.

Fossil generators were the variables in the model, and the renewables Wind Onshore, Offshore and PV the sensitivity variables. The load profile can be seen as representative for a whole year. Therefore every target number or constraint needed to be adjusted to fit the 2016 hours, that the time row covered.

5.2 Levelized cost of electricity (LCOE)

For the levelized cost of electricity (LCOE), the report by ISE was the main source of data (2020, 2030), as well as the DIW study (2050).

The ISE study also provided more specific data about the full load hours of the power plants depending on the location of the generation. (Held, et al., 2014) The costs were calculated according to (6) and were taken directly from the ISE study. More on the calculation itself can be found in chapter 3 of this thesis. The study used data for the FLHs, that was determined through a detailed resource analysis in the report by Held et. al. This calculation is an important base for the calculation of potential and costs in specific areas. The focus is set on solar and wind technologies, as the price of those technologies is strongly influenced by the resources available at the location.

The workflow used by Held et al. for the analysis is shown in Figure 10. A more comprehensive description of this analysis can be found in the cited ISE study.

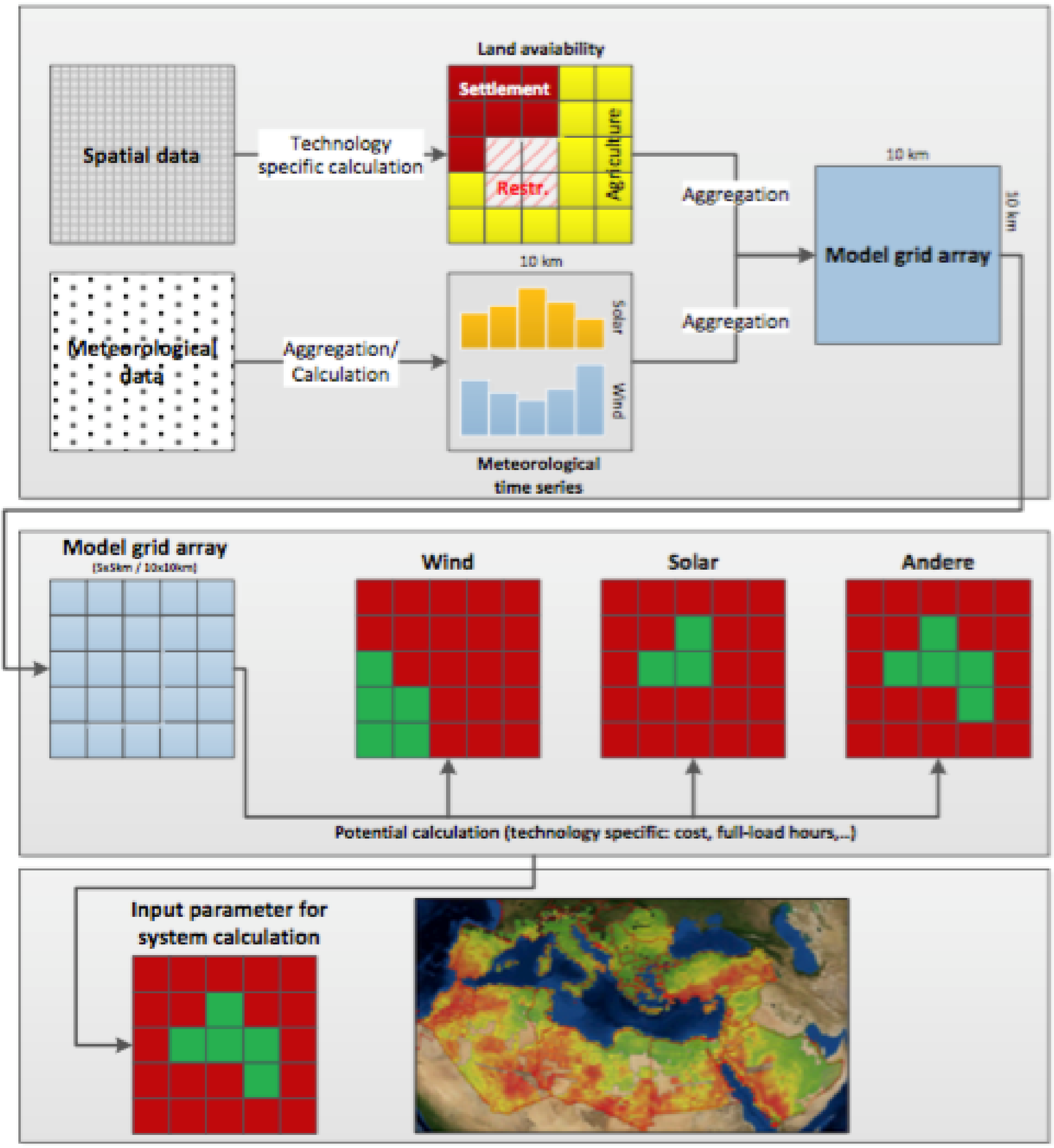


Figure 10: Workflow structure of the resource analysis used in (Held, et al., 2014)

The results show a range of FLHs for every country of Europe. For Germany, these values can be found with the index “DE”, and suggest a low potential for Onshore

Wind, a medium potential for Offshore Wind and a high potential for PV, as seen in Table 10.

Table 10: Potential of selected RES with corresponding FLHs (Held, et al., 2014)

Technology	Wind speed/solar radiation	Corresponding country (on average)	FLH lower range	FLH higher range
Wind Onshore	low	AT, BG, CY, CZ, DE, EE, FI, IT, LU, LV, PT, RO, SK, SL, ES	1500	2200
	medium	BE, HR, DK, FR, GR, HU, LT, MT, NL, PL, SE	2200	2600
	high	IR, UK	2600	3000
Wind Offshore	low	CY, GR, SE	2800	3100
	medium	BE, FR, DE, MT, PL	3100	3400
	high	DK, IR, NL, UK	3400	4000
PV	low	FI, SE	600	800
	medium	BE, CZ, DK, EE, IE, LV, LU, NL, PL, UK	800	1000
	high	AT, BG, HR, FR, DE, HU, RO, SK, SL	1000	1200
	very high	CY, GR, IT, MT, PT, ES	1200	1500

For the 2050 cost data, a study by the German Institute for Economic Research DIW was the main source. Conducted in 2013, it offers a comprehensive outlook for cost parameters in the energy sector. Due to the fact that most literature used European data, the results can best be applied to models with a European geographical background.

Those full load hours from Table 10 were used to calculate the remaining projected costs of wind and PV for 2050, as the DIW study only provided investment cost, operating cost and variable cost data, as well as a lifetime, which was necessary for the calculation of the annuity factor.

Table 11: Cost data for RES for 2050 (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013)

	Capital costs in €/kW	Variable O&M costs in €/MWh/a	Fixed O&M costs in €/kW/a	Lifetime in years
Wind Onshore	1075	-	35	25
Wind Offshore	2093	-	80	25
PV	425	-	25	20

Since the Onshore wind turbines are a relatively mature technology, learning rates lower than for Offshore turbines can be expected. This is reflected by the development of the capital costs over time, with the Onshore turbines seeing a decrease of 17.32% from 2010-2050 and the Offshore turbines almost twice the decrease of 30.23%. (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013)

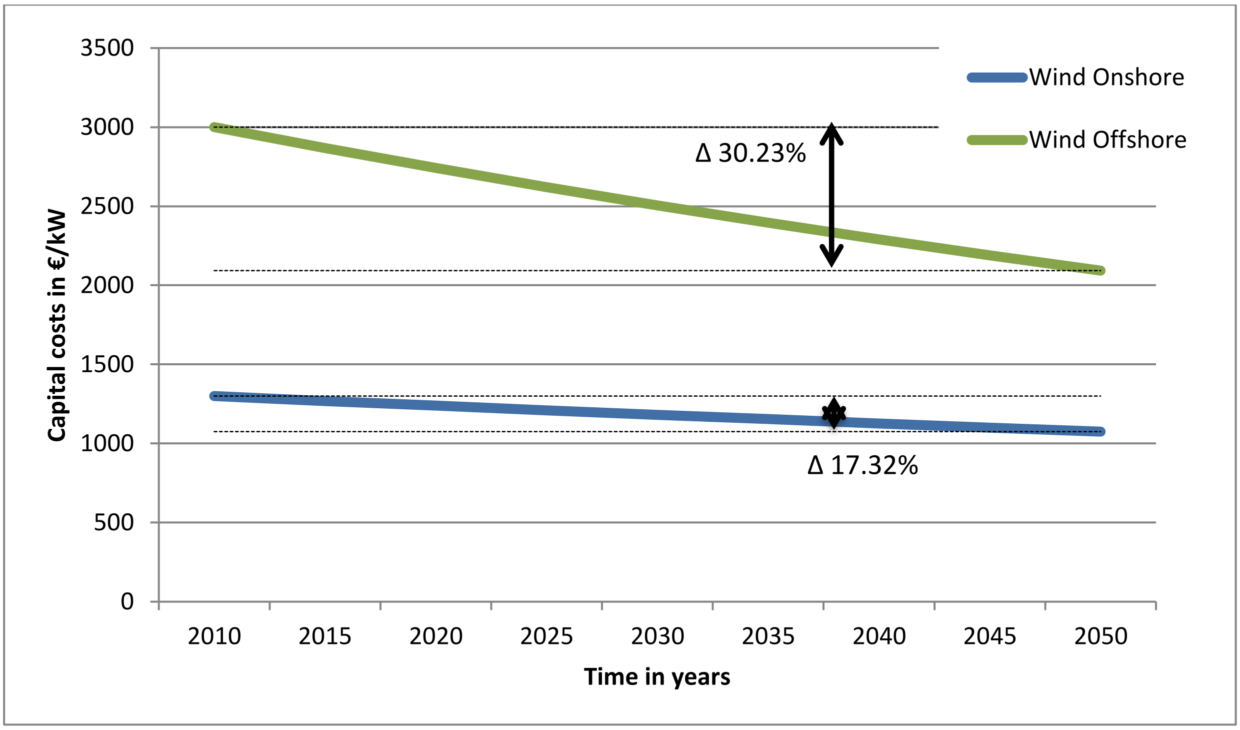


Figure 11: Development of capital costs for Wind Onshore and Offshore from 2010-2050 (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013)

Table 12: Development of capital costs for Wind Onshore and Offshore from 2010-2050

Capital Costs in €/kW	2010	2015	2020	2025	2030	2035	2040	2045	2050
Wind Onshore	1300	1269	1240	1210	1182	1154	1127	1101	1075
Wind Offshore	3000	2868	2742	2621	2506	2396	2290	2189	2093

PV modules saw significant price reductions in the past few years, a number of studies was conducted on this development. The data used for this thesis is compiled out of these studies and includes different technologies, power plant sizes and types of power plants (open area or building). Since 2008 price reductions of 15% were observed, with learning rates around 20%. This may drop to about 5% and and a learning rate of 14-18% in the near future, according to Schroeder et al. The 72.78% reduction of capital costs from 2010-2050 reflects those rates.

Table 13: Development of capital costs for PV from 2010-2050 (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013)

Capital Costs in €/kW	2010	2015	2020	2025	2030	2035	2040	2045	2050
PV	1560	950	750	675	600	555	472	448	425

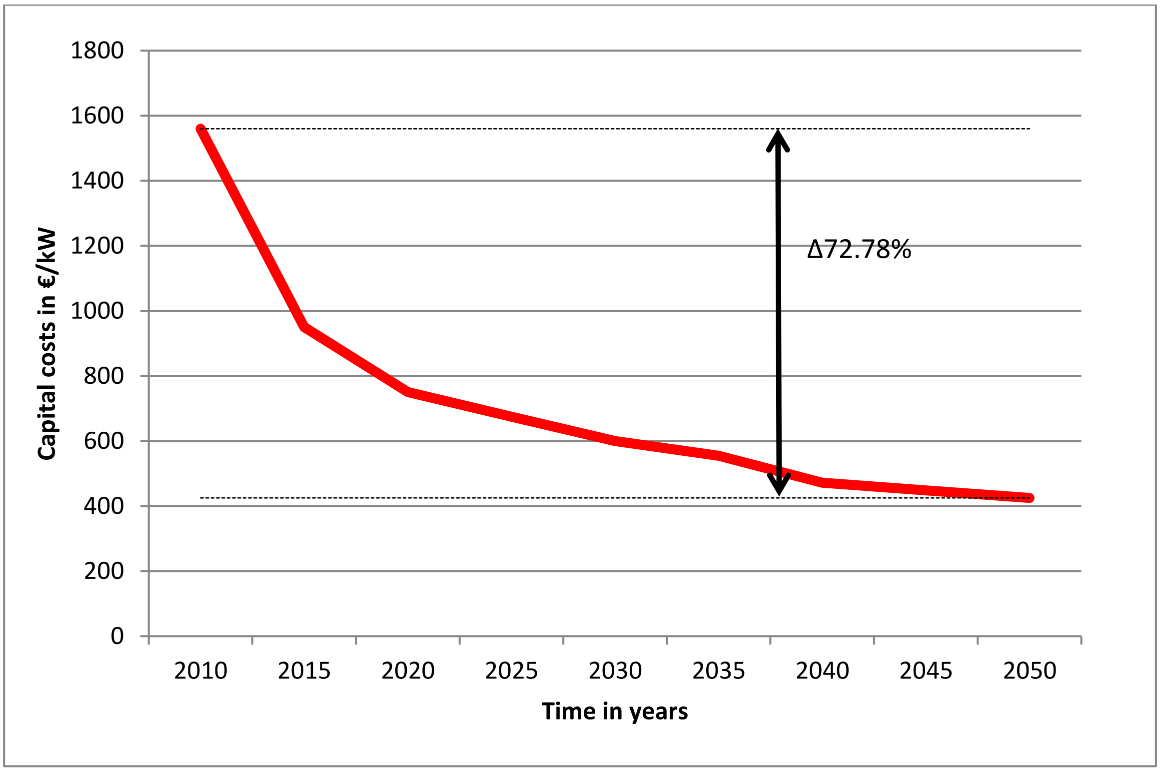


Figure 12: Development of capital costs for PV from 2010-2050 (Schröder, Kunz, Meiss, Mendelevitch, & von Hirschhausen, 2013)

The LCOE of 2050 for each techology was calculated according to Formula (6).

With the assumption of a 7% interest rate and the data from the DIW outlook and the ISE study, the following LCOE for wind onshore, offshore and PV were determined and used for the calculation of the abatement costs.

in €/MWh	2020 (Held, et al., 2014)	2030 (Held, et al., 2014)	2050
Wind Onshore	131 - 75	125 - 70	84,8 - 57,8
Wind Offshore	131 - 93	121- 83	83,7 - 76,4
PV	195 - 93	170 - 83	61,5 - 51,1

Table 14: LCOE of Wind Onshore, Offshore and PV until 2050

Since there was no demand or renewable generation data available for 2040, this moment of time was not considered in the calculation of MACs in the following chapter.

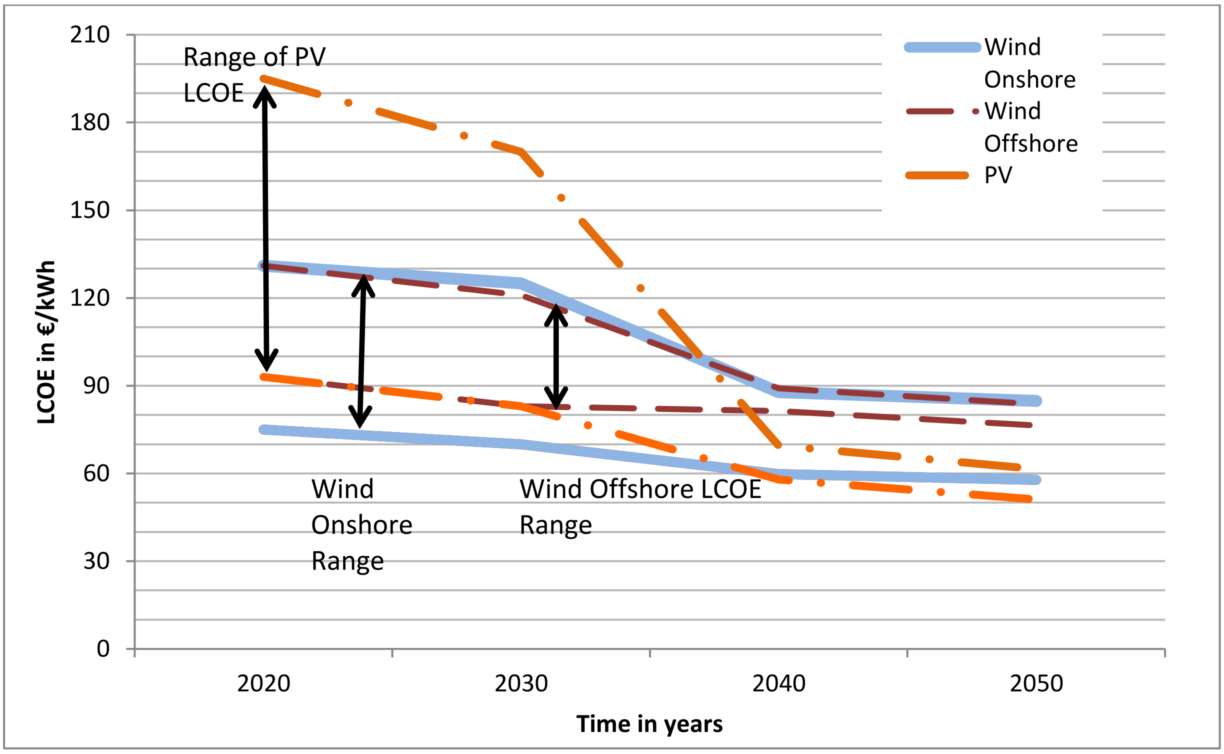


Figure 13: Possible development of LCOE for Wind Onshore, Offshore and PV

5.3 CO2 emission allowance price & fuel costs

For the possible CO2-price development this paper uses two scenarios:

Firstly the European Union´s Reference 2016 Scenario (ref16), which is a benchmark scenario published by the European Comission in 2016, that reflects the current policy of the EU.

Secondly the so-called EUCO-27 scenario, which is based on the ref16-scenario and was created through PRIMES and aims at the modelling of a possible way to reach the 2030 targets for climate and energy, together with an energy efficiency target of 27%.

Those climate and energy targets were set by the European Comission in 2014. (European Commission, 2014) The EUCO-scenarios set targets for 2030 and 2050, and set decarbonization goals in line with a 2 degrees global scenario and the intended contribution of GHG reduction according to the 2015 Climate Conference in Paris. (Capros, 2017)

The PRIMES model projects energy demand, supply prices and investment of the whole energy system of the European Union, as well as for every country individually. From a mathematical point of view, PRIMES is solving a so-called EPEC problem (equilibrium problem with equilibrium constraints), through which prices can be determined explicitly. (E3M Lab, 2013)

The used CO2-price estimations are shown in Table 15 and also in Figure 14, together with the assumptions for fuel prices.

Table 15: CO2-permission prices and fuel costs until 2050

in €/tCO2	2020	2025	2030	2040	2050
Reference 16	10	30	40	95	264
EUCO-27	10	10,3	10,8	54,9	152,4
Coal in €/MWh prim	8,4	10,1	12,1	13,3	14,2
Gas in €/MWh prim	28,4	30,7	33,4	36,9	38,2

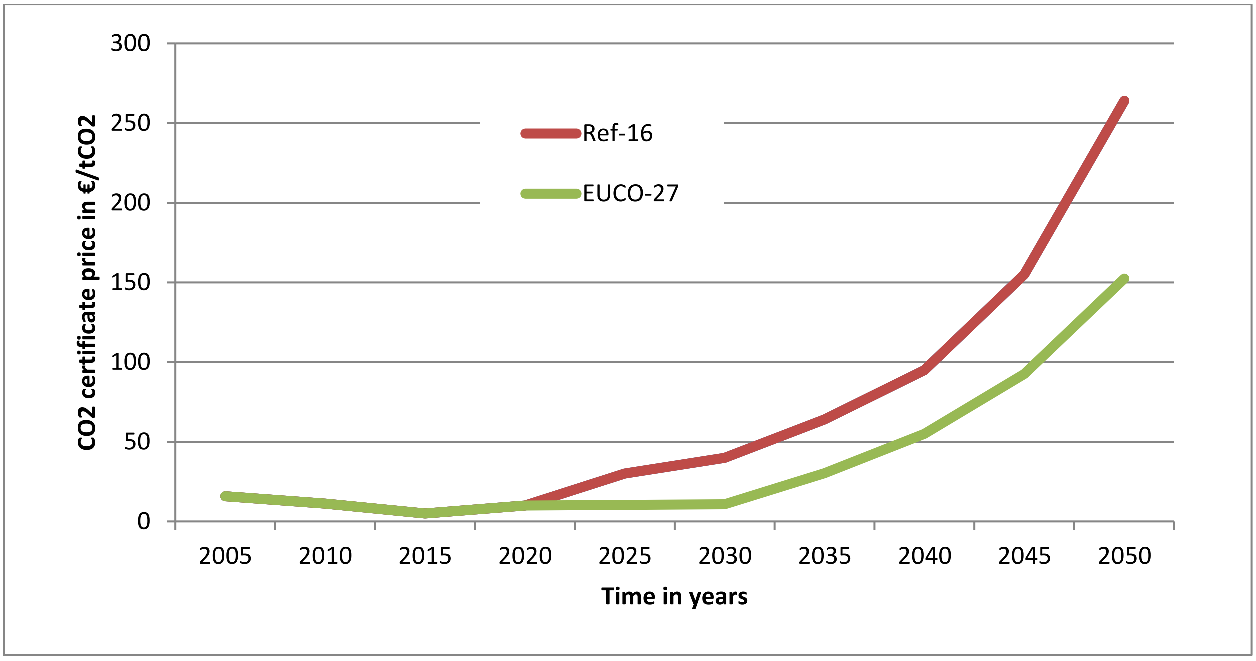


Figure 14: CO2 emission allowance price development for two scenarios

5.4 CO2 - Limits

To make sure that emission targets are fulfilled, a CO2-Budget was introduced into the MATLAB optimization model. These figures were taken from a study by the Fraunhofer Institute and the Öko-Institute. The central questions this study tried to answer, was how much CO2 can be abated with current (2012) measurements and which strategies or measurements are necessary to reach climate goals. (Ziesing, et al., 2015)

Two scenarios were included into this thesis:

- a business-as usual scenario (AMS), that included all measurements taken until October 2012 and continued them until 2050. It represents the state-of-the-art of climate and energy policy framework.
- a climate protection scenario (KS80), that looked for an overall 80% reduction of CO2-emissions in Germany. Only targets for the energy-generating sector were considered for this thesis.

Table 16: CO_2 emission targets for the corresponding years (Ziesing, et al., 2015)

in Mt CO_2	2020	2030	2050
AMS scenario	317.364	285.455	170.265
KS80 scenario	256.696	182.179	42.336
AMS (for 12 weeks)	73.236	65.87	39.29
KS80 (for 12 weeks)	59.076	42.04	9.76

The MATLAB model includes the respective emission targets for 12 weeks, since there is only data available for this time frame.

6 Results

In this chapter the results of the MATLAB model and the following calculations will be presented and explained. For each technology (Wind Onshore, Wind Offshore and PV) a graph is constructed to give a better idea of the respective development of CO2 abatement costs. Since some studies see the MAC as the ideal point for carbon allowance prices, the two scenarios for CO2-certificates, EUCO-27 and Ref-16, are included as well.

The results should be interpreted more as trends, than as exact number, as a number of simplifications have been made and, as always with future developments, not all insecurities can be calculated in.

6.1 Wind Onshore

According to the workflow in chapter 3, the MATLAB model was executed two times with the following results for CO2 emissions and MV.

Table 17: MATLAB results for WInd Onshore from 2020-2050

	2020	2030	2050
CO2 emissions baseline in tCO2	29.019	27.301	5.3569
CO2 emissions 10% extension in tCO2	28.399	26.235	4.5563
MV in €/MWh	23	32.25	67.248

Together with the data for LCOE in Table 14, the MAC for Wind Onshore were calculated according to the formulas (5) and (7).

Table 18: MAC for Wind Onshore from 2020-2050

in €/tCO2	2020	2030	2050
Low FLHs	308.91	265.2	100.66
High FLHs	148.73	107.94	-53.90

The results for the CO2-abatement costs of Wind Onshore in comparison to the CO2-price scenarios Reference 16 and EUCO-27 are shown in Figure 15.

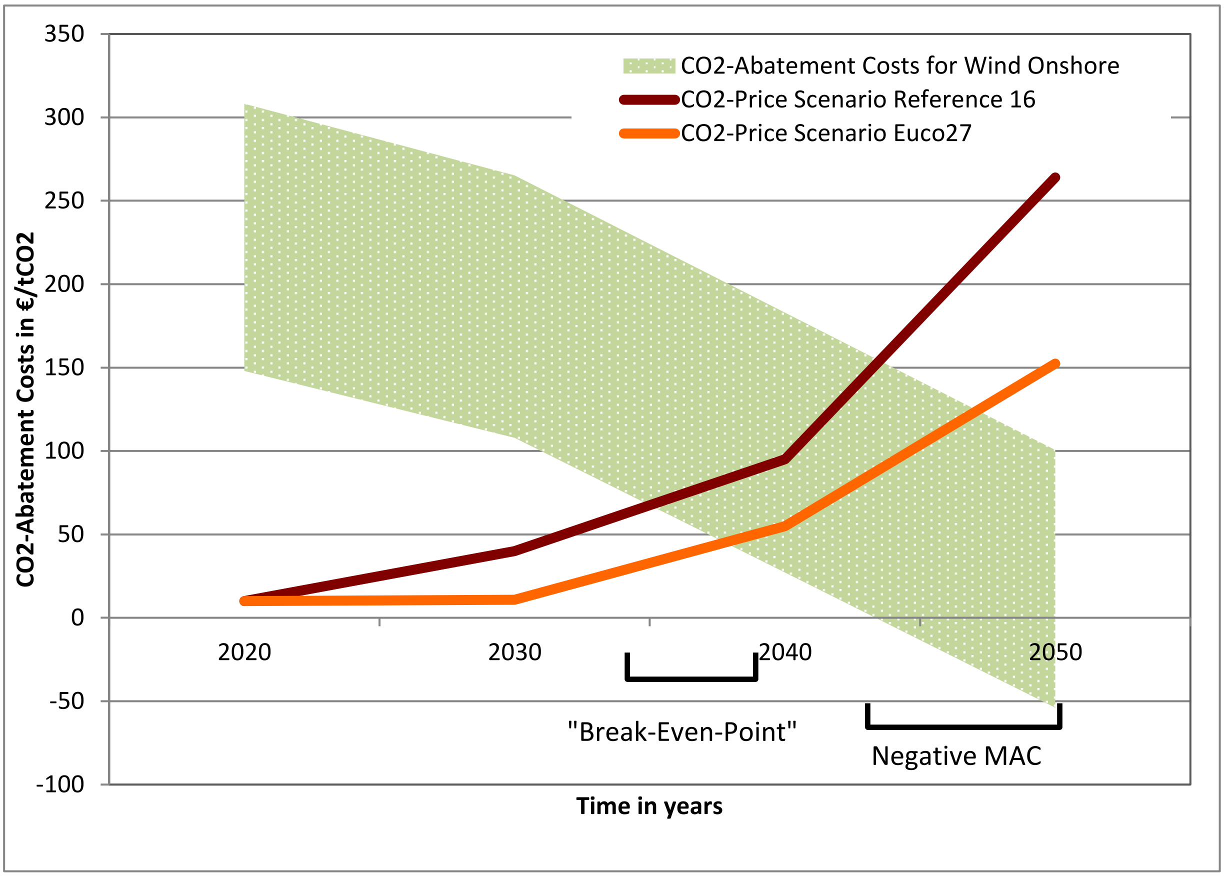


Figure 15: Development of CO2-Abatement costs for Wind Onshore until 2050

As mentioned above, the range of abatement costs is a result of the different site potentials of wind power plants, which leads to different FLHs and therefore different LCOE. The upper border of the green area represents low FLHs, the lower border high FLHs.

As of 2020, the model showed a high need for supporting measures in deploying the technology, as the MAC are very highly positive (308.91 – 148 €/tCO2) and therefore not economically viable. Also the expected revenue by the ETS is very little, when compared to the MAC, due to the very low EUA prices of 10 €/tCO2.

Until 2030 there´s only a slight decrease due to technological learning, however, together with a surging price for carbon certificates to over 50 €/tCO2, a complete phase out of support measures for promising sites with large FLHs can be expected around 2035. This “Break-Even-Point” is reached when the price for EUAs is larger than the MAC of a specific power plant location. Even though the MACs are still positive at this point, the revenue from the ETS weighs outweighs the investment made.

Between 2040 and 2050 even sites with less yield could operate economically without additional governmental support, as prices for EUAs increase even further, up to 264 €/tCO_2 (ref-16) or 152.4 €/tCO_2 (EUCO-27) in 2050, accelerating the shift from fossil generators to RES.

High potential sites (FLHs of 2200 h/a) are expected to reach negative abatement costs in the years after 2040 - 2045, which means that a further deployment of this technology would be economically viable even without an ETS in place. In this model this situation occurs, when the MV for a scenario is higher than the LCOE of the technology.

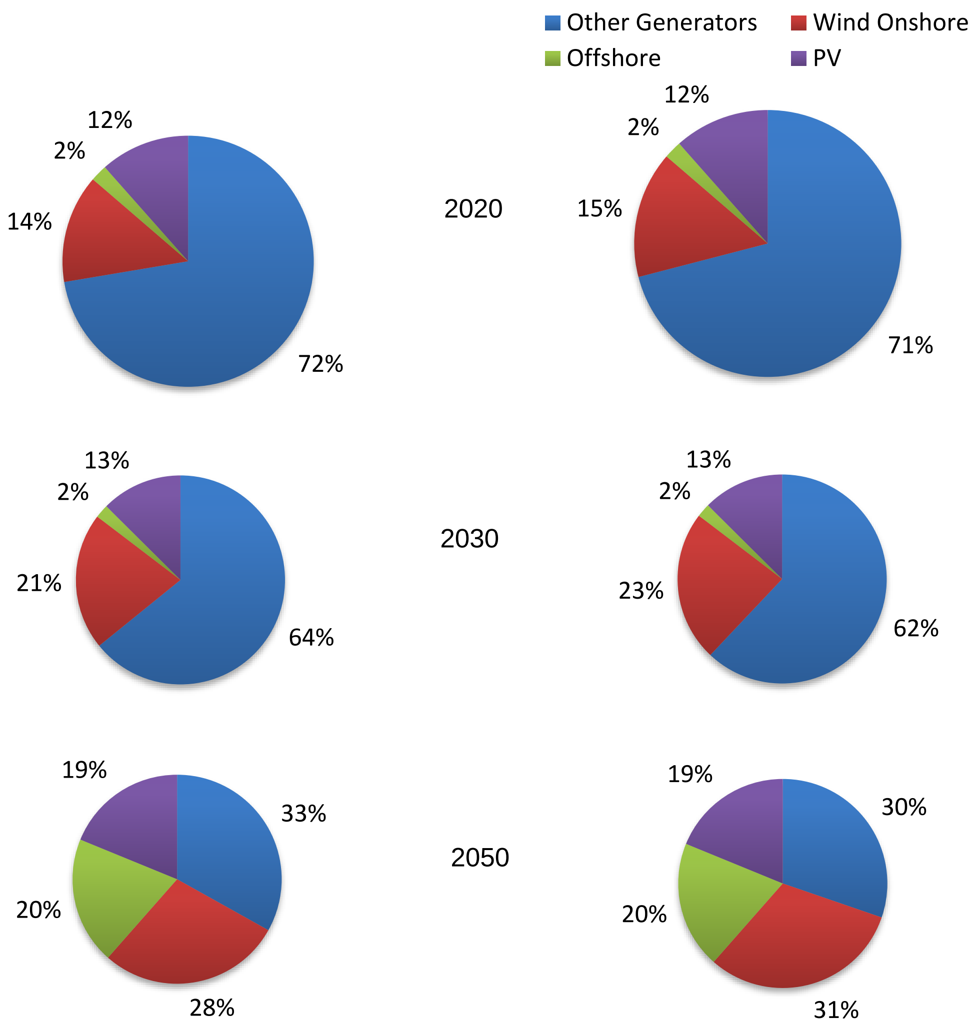


Figure 16: Comparison of generation mix before and after additional extension of Onshore Wind

Figure 16 and Table 19 show how the generation mix changes when the necessary extension to calculate the abatement costs for each year is made. On the left side the base scenario is shown, on the right the generation mix in the respective year after the 10% extension of wind is shown.

The "other generators" are mainly fossil generators, but also contain other generators like run-of-river, storage, nuclear (in 2020) and import/export. For simplicity reasons and to give a better insight, those are summarized. When comparing the generation mix of each year, the observation can be made, that the further extension brings the necessary marginal change in the percentage of the mainly fossil generators. Therefore a slight change in emissions is the result.

Table 19: Generation mix for Wind Onshore extension from 2020-2050

in TWh	2020	Δ+10%	2030	Δ+10%	2050	Δ+10%
Other Generators	100.81	98.86	92.23	89.18	53.46	48.88
Wind Onshore	19.45	21.39	30.48	33.52	45.83	50.41
Offshore	3.01	3.01	3.03	3.03	31.81	31.81
PV	16.06	16.06	18.02	18.02	30.37	30.37
Total load coverage	139.37	139.37	143.76	143.76	161.48	161.48

Notable is the change in the share of Onshore Wind, as it changes from about 14% in 2020, to about 30% in 2050, which makes it one of the most important contributors on a road to a decarbonized power generation. Figure 17 shows the development of the respective shares of generators in comparison with the total generation for each year and scenario.

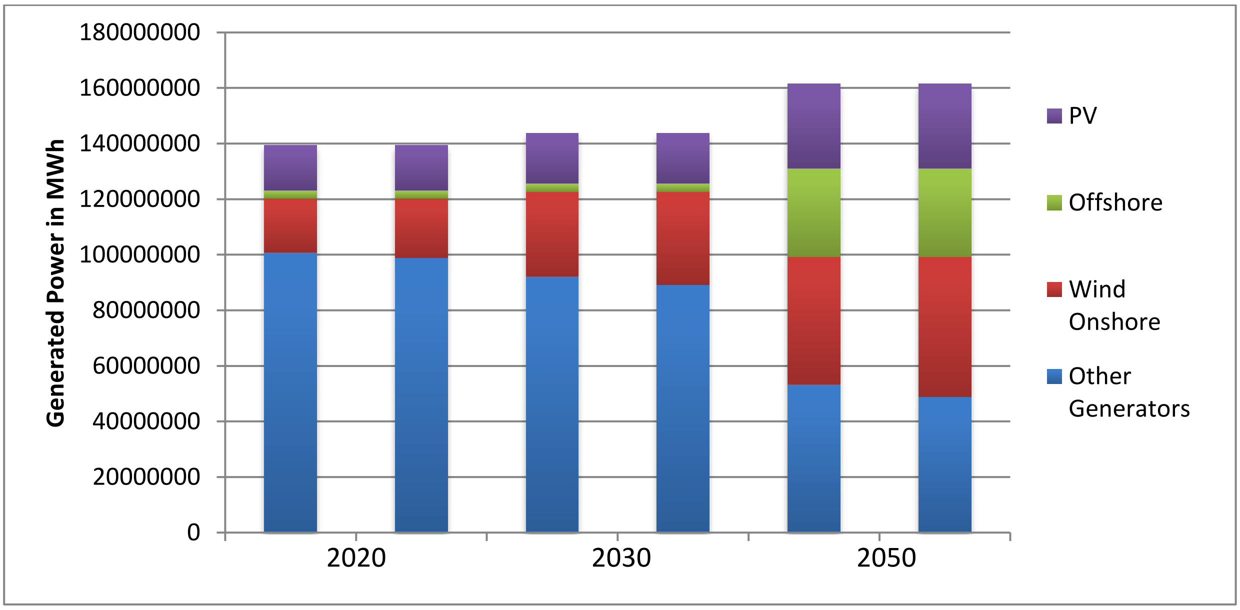


Figure 17: Total generation mix for Wind Onshore from 2020-2050

6.2 Wind Offshore

For Wind Offshore the following results from the MATLAB model were used to construct the diagram of the MAC.

Table 20: MATLAB results for Wind Offshore from 2020-2050

	2020	2030	2050
CO_2 emissions baseline in tCO_2	29.019	27.301	5.3569
CO_2 emissions 10% extension in tCO_2	28.194	27.196	4.7206
MV in €/MWh	23	32.25	67.248

Together with the data for LCOE in Table 14, the MAC for Wind Offshore were calculated according to the formulas (5) and (7).

Table 21: MAC for Wind Offshore from 2020-2050

in €/tCO_2	2020	2030	2050
Low FLHs	309.4	255.78	82.47
High FLHs	200.54	146.26	45.52

The results for the CO_2-abatement costs of Wind Offshore in comparison to the CO_2-price scenarios Reference 16 and EUCO-27 are shown in Figure 18.

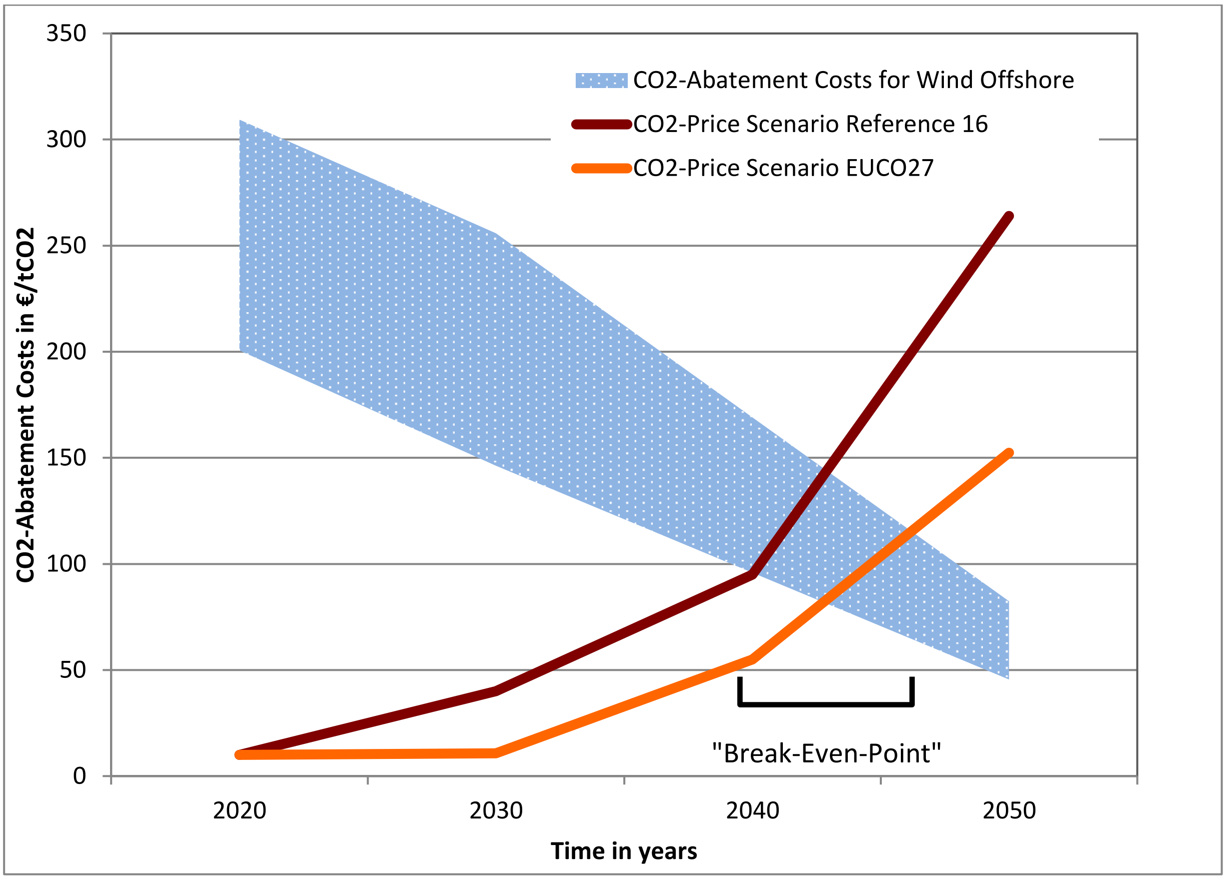


Figure 18: Development of CO2-Abatement costs for Wind Offshore until 2050

The borders of the blue area represent MAC for high potential power plant sites (upper border) and lower potential sites (lower border).

At the starting point of the examined time period in 2020, similar to Wind Onshore, supporting measures like FITs are very much needed, to finance and operate a power plant economically. CO2-prices are expected to be very low (10 €/tCO2) compared to the MAC (200.54 – 309.4 €/tCO2), as seen in the diagram. Due to technological learning the LCOE and, as a result, the MAC is decreasing almost constantly. The progression of the diagram shows that locations with high FLHs could reach their “Break-Even-Point” around 2040 and start to be economically viable, depending on the CO2-price (upper border of the blue area).

Less promising sites´ investment will be outweighed, when the CO2-price is higher than the MAC. This can be expected between 2040 and 2045, when looking at the diagram. (lower border of blue area) Those time frames are highly dependent on the LCOE development as well as on CO2-price progress in the future. Therefore a certain level of uncertainty has to be taken into consideration.

Worth mentioning is the narrowing of the cost range, which is mainly due to the smaller range of FLHs for offshore wind power plants. The costs for them remain higher, when compared to the onshore technology.

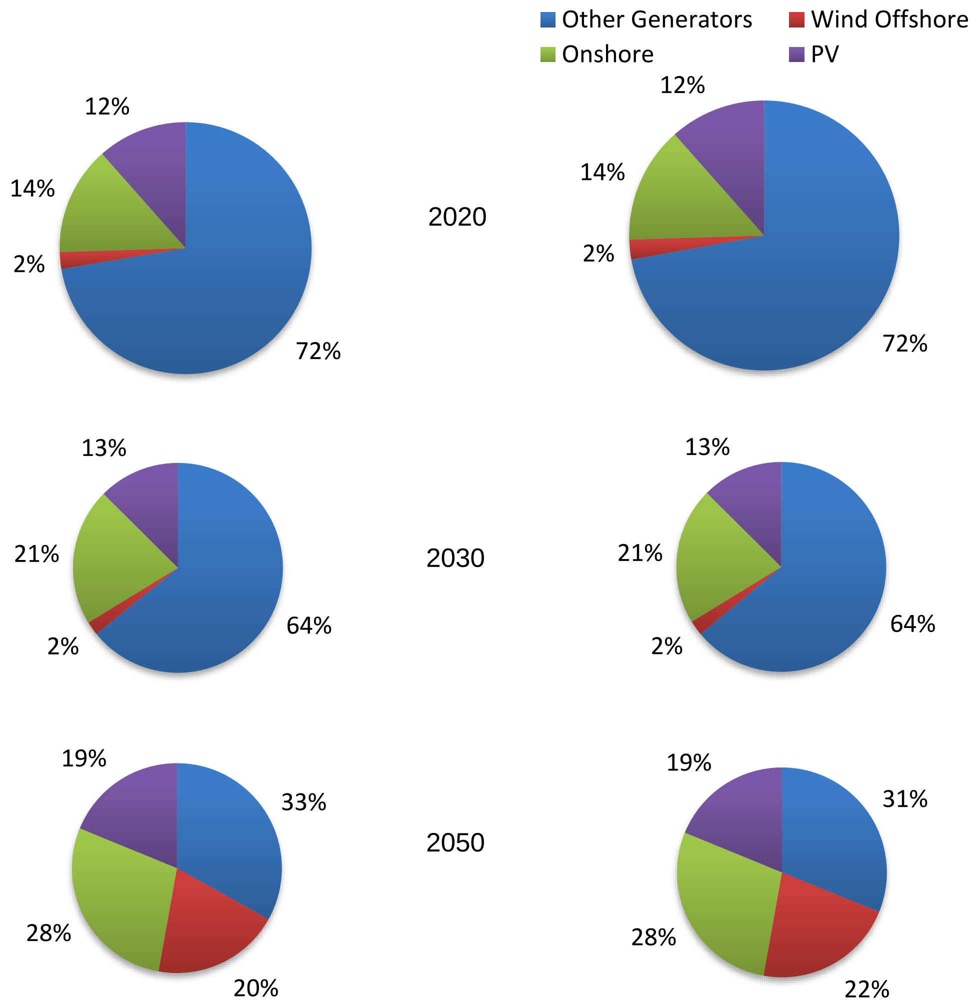


Figure 19: Comparison of generation mix before and after additional extension of Offshore Wind

How the generation mix changes, when the data for the abatement costs of offshore wind are determined, can be seen in Figure 19 and Table 22. On the left of the Figure the base scenario is shown, the right side shows the mix for a 10% extension of offshore wind.

While offshore wind only represents a marginally low share of load coverage (2%) in 2020, this changes between 2020 and 2050, when carbon permission prices rise and abatement costs begin to significantly fall, making the technology economically viable, when also considering ETS revenue. As of 2050 about one fifth (20-22%) of the power generation is expected to come from offshore wind power plants, according to the MATLAB calculations and the input data by the EEG.

Table 22: Generation mix for Wind Offshore from 2020-2050

in TWh	2020	Δ+10%	2030	Δ+10%	2050	Δ+10%
Other Generators	100.81	100.81	92.23	91.93	53.46	50.28
Wind Offshore	3.01	3.3	3.03	3.32	31.8	34.99
Onshore	19.45	19.45	30.48	30.48	45.83	45.83
PV	16.06	16.06	18.02	18.02	30.37	30.37
Total load coverage	139.37	139.37	143.76	143.76	161.48	161.48

Since the total generation from offshore is on comparably low levels, the necessary 10% extension does not have a great impact on the amount of CO_2 emitted in the examined time period in 2020 and 2030. At 2050 this impact is much larger, resulting in higher CO_2-savings per additional MWh renewable energy, as seen in Table 20.

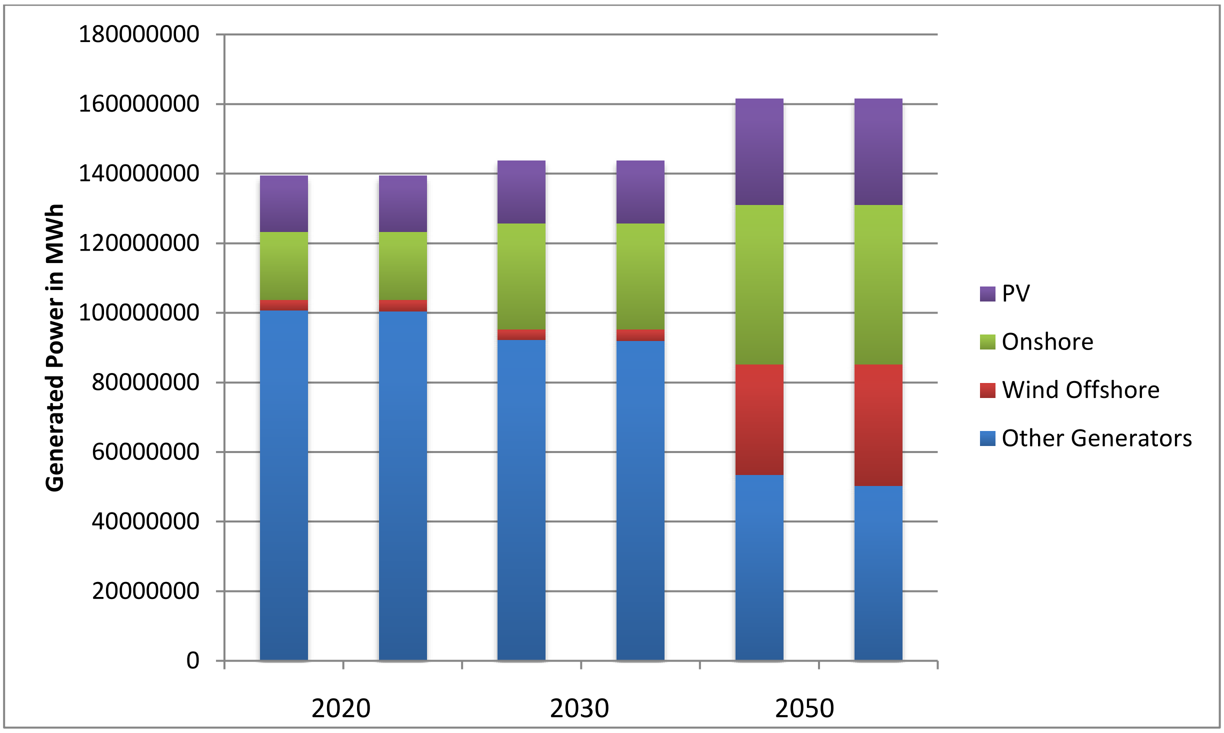


Figure 20: Total generation mix for Wind Offshore extension scenario from 2020-2050

When looking at Figure 20 an increase of the Offshore share can be seen in absolute numbers. Note that these numbers represent the electricity generated in a 12 week period.

6.3 Photovoltaics (PV)

For Wind Offshore the following results from the MATLAB model were used to construct the diagram of the MAC.

Table 23: MATLAB results for PV from 2020-2050

	2020	2030	2050
CO2 emissions baseline in tCO2	29.019	27.301	5.3569
CO2 emissions 10% extension in tCO2	28.457	26.617	4.861
MV in €/MWh	23	32.25	67.248

Together with the data for LCOE in Table 14, the MAC for Wind Offshore were calculated according to the formulas (5) and (7).

Table 24: MAC for PV from 2020-2050

in €/tCO2	2020	2030	2050
Low FLHs	491.67	394.18	-35.48
High FLHs	200.1	145.22	-98.27

The results for the CO2-abatement costs of PV in comparison to the CO2-price scenarios Reference 16 and EUCO-27 are shown in Figure 21.

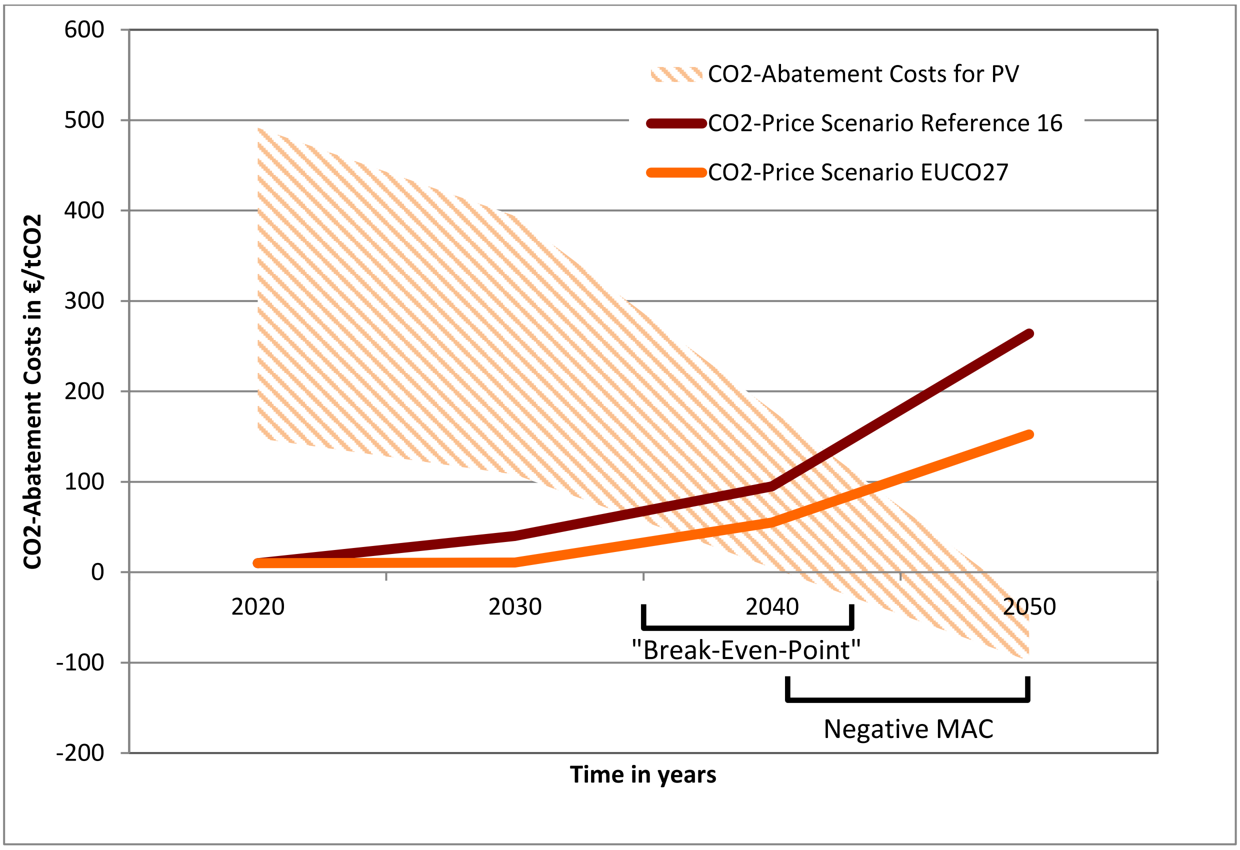


Figure 21: Development of CO2-Abatement costs for PV until 2050

The data from the MATLAB model show a large cost range for PV MAC in 2020 and 2030. This is due to the high variety of LCOE from the ISE study. Since the LCOE only depends on the FLH in 2050 in this calculation, this margin is much smaller then. As mentioned before, the calculations for the LCOE of 2050 use cost parameters from a 2012 DIW study, that average a great number of different PV technologies to one single value.

At 2020 PV requires substantial governmental support to be viable, due to highly positive MAC and very low CO2-prices. After 2030, when CO2-prices rise and the MAC starts to lower significantly, the “Break-Even-Point” might be reached around 2035 for locations with high solar radiation and FLHs (lower border of orange area). These sites could become economically independent from an ETS around 2040, when their MAC becomes negative, and, with LCOE data for 2050, would reach a value of -100 €/tCO2 at the end of the examined period for the estimation.

For sites with less potential, this point of being econimically viable could be reached after 2040, when EUA-price and MAC reach levels of about 100 €/tCO2 (see upper border of the orange area).

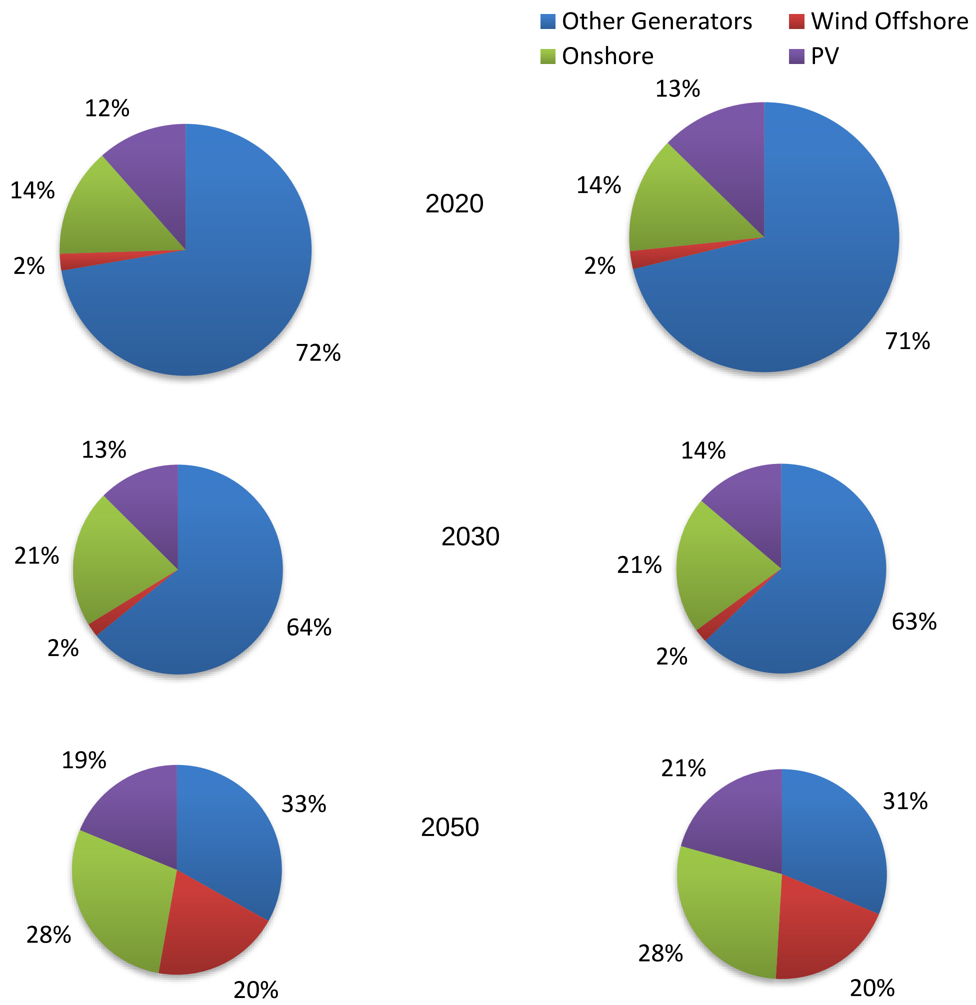


Figure 22: Comparison of generation mix before and after additional extension of PV

When executing the documented steps in MATLAB to calculate the MAC of PV, the generation mix changes according to Figure 22. In 2020, PV already is able to provide substantial load coverage (16 TWh in a 12 week period), especially during midday. While this does not change greatly until 2030 (18.02 TWh). The used data shows, that as of 2050, about a quarter of the total power generation comes from PV.

With PV already being an important technology, an extension by 10% capacity already saves a significant amount of CO_2, which would otherwise be emitted by fossil power plants like coal, gas or oil.

Table 25: Generation mix for PV extension scenario from 2020-2050

	2020	Δ+10%	2030	Δ+10%	2050	Δ+10%
Other Generators	100.81	99.20	92.23	90.43	53.46	50.43
Wind Offshore	3.01	3.3	3.03	3.32	31.8	34.99
Onshore	19.45	19.45	30.48	30.48	45.83	45.83
PV	16.06	17.67	18.02	19.83	30.37	33.41
Total load coverage	139.37	139.37	143.76	143.76	161.48	161.48

With PV already being an important technology by 2020, an extension by 10% capacity already saves a significant amount of CO_2, which would otherwise be emitted by fossil power plants like coal, gas or oil.

The increasing share of PV generation can also be seen in Figure 23. With a total demand of 161 TWh and PV covering one fifth of it in 2050, it represents another cornerstone in a shift towards a low carbon power generation mix. This shift towards more PV is favored by falling costs caused by technological learning, especially due to falling capital costs, as seen in Figure 12.

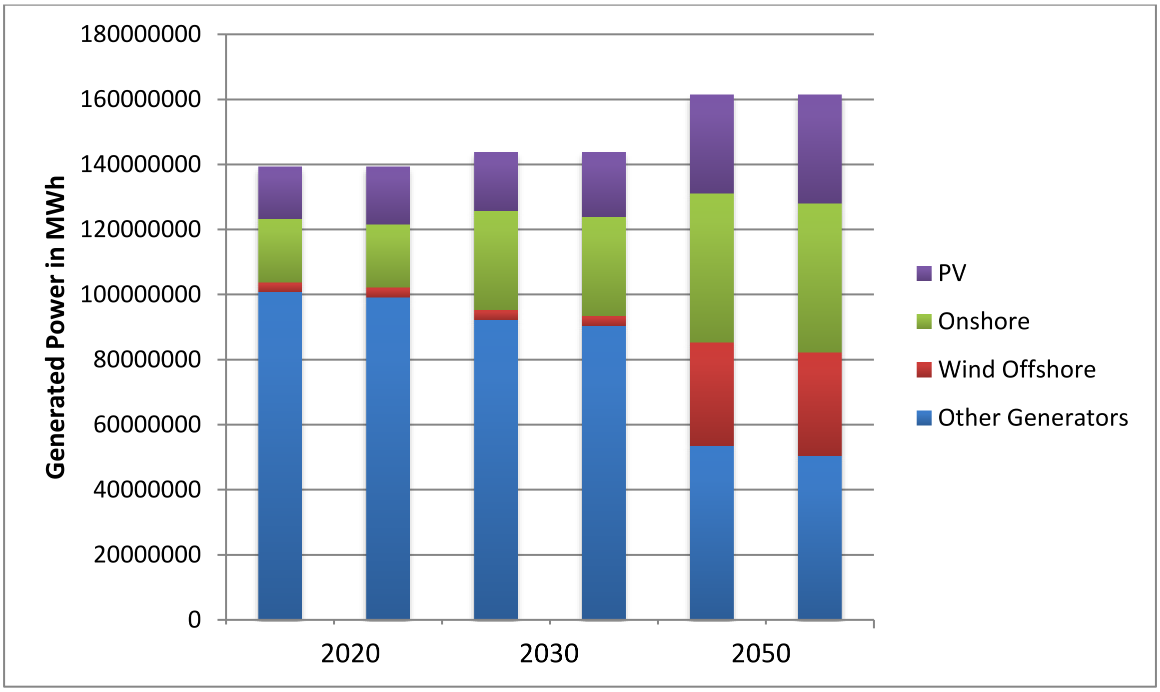


Figure 23: Total generation mix for PV extension scenario from 2020-2050

7 Conclusions

This thesis is trying to show a possible development of carbon abatement costs in Germany after 2020 towards 2050. These costs were calculated with the help of a MATLAB optimization model and the ratio between the support costs for each renewable technology and the amount of CO2 abated per MWh additionally generated by RES. As mentioned before, the results represent merely trends than exact time periods, as models for future developments, especially when going as far as 2050, are always subject to high insecurity.

These trends reflect the need for support measures for renewables and can serve as an orientation point on how much support would be needed to ensure a ongoing extension of RES. Also they show the importance of a functional and competitive ETS, that generates enough revenue to further accelerate this extension. Without prices for CO2-allowances of at least 50 €/tCO2, the costs for national economies to fulfill emission and renewable targets is simply to high. This financial burden needs to be shared with carbon-emitting industries and a high CO2 price ensures, that this share is appropriately high. This is becoming even more important with the phase-out of nuclear power in Germany, which, together with low carbon pricing, led to a substantial increase of coal-generated power and therefore emissions. This increase of coal power was already pointed out in the Mc-Kinsey study´s outlook for 2020 and 2030 (Vahlenkamp, 2007).

An increase of EUA price can be expected in the third phase of the EU ETS after 2020, when the MSR-mechanism, that was already described in a previous chapter, will be established. Together with an appropriate subsidy scheme and investment incentives for RES, this could lower the costs for renewables at a quicker rate and lead to a shift from coal to the less carbon intensive gas until 2030.

Regarding the CO2-budgets that were implemented into the model, it has to be noted, that even the unambitious baseline scenario AMS was met in 2050 for both Wind and PV. This allows the conclusion, that the load and generation data already counted in a number of asumptions for RES and GHG targets. Different CO2-prices from the two price outlooks Reference-16 and EUCO-27 did not have an impact on the MV in each of the years examined, and subsequently not on the MAC. However, a rising CO2-price had the result to a shift from coal to gas after 2030 and a coal phase-out in 2050.

The results of the model showed, that a shift from fossil-based energy generators and nuclear towards more renewable technology proves to be economically viable on the long run. Also ambitious emission targets are in range, if the right subsidies are applied, to promote a further extension of RES. The most effective, but in the short term most expensive technology to support would be PV, as an economic operation could be reached soonest. The wind technologies are expected to be more important for the grid mix, as they might cover a great part of the load by 2050.

Further studies could be conducted using different load profiles with different scenarios for the development of the grid mix in Germany, different fuel prices, CO2-Budgets and price outlooks, and LCOE data to analyze the sensitivity of the MAC for Wind and PV. Especially a scenario that involves a delayed or canceled nuclear phase-out could have a significant effect on the MAC of Wind and PV, as the nuclear power itself has great CO2-abatement potential, as the McKinsey study (Vahlenkamp, 2007) pointed out.

8 Bibliography

Abell, D., & Hammond, J. (1979). *Strategic market planning : problems and analytical approaches.* Englewood Cliffs, N.J.: Prentice-Hall.

Beer, M., Corradini, R., Gobmaier, T., & Köll, L. (2009). *CO2-Verminderung in Deutschland.* München: Forschungsstelle für Energiewirtschaft e.V.

Capros, P. (2017). *How to Meet the EU's Greenhouse Gas Emission Targets - PRIMES modelling for the Winter Package.* Retrieved from Energy Economics Group TU Vienna: https://www.eeg.tuwien.ac.at/conference/iaee2017/files/presentation/Pr_Capros_Pantelis.pdf

Criqui, P., Mima, S., & Viguier, L. (1999). Marginal abatement costs of CO emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model. *Energy Policy, 27*, 585 - 601.

Duscha, V., Held, A., & del Rio, P. (2016). *Draft Report for Task 6.4, Analysis of interactinos between renewable support and climate policies.* European IEE project towards2030-dialogue. Intelligeht Energy - Europe, ALTENER.

E3M Lab. (2013). *Primes Model.* Retrieved June 16, 2018, from European Comission: https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf

Elzen, M., Lucas, P., & Gijsen, A. (2007). *Exploring European countries' emission reduction targets, abatement costs and measures needed under the 2007 EU reduction objectives.* Bilthoven: Netherlands Environmental Assessment Agency (MNP).

European Commission. (2014, October 15). *European Commission*. Retrieved June 12, 2018, from Energy modelling: https://ec.europa.eu/energy/en/data-analysis/energy-modelling

European Commission. (2015). *EU ETS Handbook.* Retrieved 04 19, 2018, from https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf

Fisher, B., Nakicenovic, N., Metz, B., Davidson, O., Bosch, P., Dave, R., & Meyer, L. (2007). *Issues related to mitigation in the long term context. Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the*

Intergovernmental Panel on Climate Change. . Cambridge: Cambridge University Press.

Fleischhacker, A. (2016). *Investments and Revenues in Electricity Markets - A Market and System Perspective.* Lecture presentation, Technical University of Vienna, Energy Economics Group, Vienna.

Fraunhofer ISE. (2015). *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.* Berlin: Study on behalf of Agora Energiewende.

Grübler, A. (1998). *Technology and Global Change.* Laxenburg: IIASA.

Held, A., Ragwitz, M., Eichhammer, W., Sensfuss, F., Pudlik, M., Pfluger, B., & Resch, G. (2014). *Estimating energy system costs of sectoral RES and EE targets in the context of energy and climate targets for 2030.* Fraunhofer ISI, TU Vienna, IIT Comillas, Fraunhofer ISE, Prognos, ECN. BMWI.

IEA. (2000). *Experience Curves for Energy Technology Policy.* Paris: OECD.

Jansen, A., Molly, J., & Neddermann, B. (2005). *dena-Netzstudie: Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020.* Köln: DENA.

Junginger, M., de Visser, E., Hjort-Gregersen, K., Koorneef, J., Raven, R., Faaij, A., & Turkenburg, W. (2006). Technological learning in bioenergy systems. *Energy Policy, 34*, 4024-4041.

Junginger, M., Faaij, A., & Turkenburg, W. (2005). Global experience curves for wind farms. *Energy Policy, 33*, 133-150.

Kuik, O., Brander, L., & Tol, R. S. (2008). *Marginal Abatement Costs of Carbon-Dioxide Emissions: A Meta-Analysis.* Institute for Environmental Studies, VU University Amsterdam. Amsterdam: ESRI.

Li, S., Zhang, X., Gao, L., & Jin, H. (2012). Learning rates and future cost curves for fossil fuel energy systems with CO 2 capture: Methodology and case studies. *Applied Energy, 93*, 348-356.

Marcantonini, C., & Ellerman, A. D. (2013). *The Cost of Abating CO2 Emissions by Renewable Energy Incentives in Germany.* MIT Center for Energy and Environmental Policy Research. MIT Climate Policy Research Unit, European University Institute, Italy .

Nakata, T., Sato, T., Kusunoki, T., & Furubayashi, T. (2011). Modeling technological learning and its application for clean coal technologies in Japan. *Applied Energy, 88*(1), 330-336.

Neij, L. (1999). Cost dynamics of wind power. *Energy, 24*(5), 375-389.

Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., & von Hirschhausen, C. (2013). *Current and Prospective Costs of Electricity Generation until 2050.* Berlin: DIW.

Shenggyuan, X., & Lam, J. (2008). A survey of linear matrix inequality techniques in stability analysis of delay systems. *International Journal of Systems Science, 39*(12), 1095-1113.

Twidale, S. (2018, August 15). *Reuters*. (A. Croft, Editor) Retrieved September 24, 2018, from What is driving a rally in EU carbon permit prices?: https://www.reuters.com/article/us-eu-carbon-rally/what-is-driving-a-rally-in-eu-carbon-permit-prices-idUSKBN1L015Y

Vahlenkamp, T. (2007). *Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland - Sektorperspektive Energie.* Düsseldorf: McKinsey and Company, Inc.

von Asselt, H., & Biermann, F. (2007). European emissions trading and the international competitiveness of enery-intensive industries: a legal and political evaluation of possible supporting measures. . *Energy Policy, 35*, 497-506.

Watkiss, P. (2005). *The Social Cost of Carbon. The Social Costs of Carbon (SCC) Review – Methodological Approaches for Using SCC Estimates in Policy Assessment .* Didcot, UK: AEA Technology Environment .

Ziesing, H.-J., Repenning, J., Emele, L., Blanck, R., Elsland, R., Braungardt, S., & Eichhammer, W. (2015). *Klimaschutzszenario 2050 - Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit.* Berlin: Öko Institut e.V.

9 Index of Figures

10 Index of Tables

11 Index of Formulas

12 Abbreviations

CCGT	Combined Cycle Gas Turbine
EC	European Comission
EEG (ger.)	Erneuerbare Energie Gesetz (dt.)
ETS	Emission Trading System
EU	European Union
EUA	European Emission allowance
FIT	Feed-in tariff
GDP	Gross domestic product
GHG	Greenhouse gas
LCOE	Levelized cost of electricity
LR	Learning rate
MAC	Marginal Abatement Cost
OCGT	Open Cycle Gas Turbine
PR	Progress rate
PV	Photovoltaics
RES	Renewable energy sources
FLH	Full load hour
MV	Market value
EEG	Energy Economics Group
TU	Technical University