Modelling offshore wind in the IMAGE/TIMER model

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Abstract

Current global energy consumption is expected to continue to grow as the global population is likely to increase towards 9 billion in 2050 while income levels per capita surge with 3-5% per year. Resource depletion, climate change, air pollution and energy security are several reasons to assume that these energy trends are unsustainable. The IMAGE/TIMER model was developed to gain more insight and understanding in the global environmental system. So far, offshore wind power was not taken into account in the projections. This study investigates how offshore wind power can be modelled in the IMAGE/TIMER framework and the impact of this technology on the electricity production in case of different scenarios.

As the offshore wind industry bears great similarity with the onshore wind industry, the technology is modelled such that the specific investment costs are split up into two parts. The first part is similar to the cost of onshore wind, while the second part is the additional costs to place wind farms offshore. This distinction is also implemented in the concomitant learning and depletion effects. Global offshore wind potential estimations were collected in collaboration with the National Institute of Renewable Energy. Cost data was estimated on the basis of the installed wind farms in Western Europe in the past two decades.

The inclusion of offshore wind in a baseline scenario resulted in an additional 1445 GW of extra renewable electricity generation capacity compared to a situation without offshore wind. This leads to 44% increase of the global renewable electricity production share and a 4% decrease in the annual CO_2 emissions in 2100. Modelling results show that offshore specific policy measures had a strong positive effects on the price development in the period 1990 – 2010 but lacks significant response in later periods. In a 2°C climate target scenario with a compatible carbon tax path the inclusion of offshore wind ensures a 44% increase in the share of renewable energy production. Offshore wind takes op 35% of the total installed renewable generation capacity.

Overall, it can be concluded that the impact of offshore wind technology on the global electricity system is significant and that it is likely that it may contribute considerably to reverse several of the unsustainable energy trends.

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AEEI	*Autonomous Energy Efficiency Increase*
CCS	*Carbon capture an storage*
CHP	*Combined heat and power*
CO2	*Carbon dioxide*
COE	*Cost of electricity*
EEZ	*Exclusive economic zone*
EJ	*Exajoule*
EPG	*Electricity power generation*
GW	*Gigawatt*
IMAGE	*Integrated Model to Assess the Global Environment*
IPCC	*Intergovernmental Panel on Climate Change*
kW	*Kilowatt*
kWh	*Kilowatthour*
MNL	*Multinomial logit*
MW	*Megawatt*
NCEAS	*National Center for Ecological Analysis and Synthesis*
NOAA	*National Oceanic and Atmospheric Administration*
NREL	*National Renewable Energy Laboratory*
O&M	*Operation and maintenance*
PIEEI	*Energy efficiency improvement*
PJ	*Petajoule*
PR	*Progress Ratio*
SRES	*Special Report on Emissions Scenarios*
TIMER	*The IMage Energy Regional model*
TW	*Terawatt*
UNEP	*United Nations Environment Programme*
ZJ	*Zettajoule*

1 Introduction

Current global energy consumption is around 500 exajoule (EJ) and has been growing, on average, by about 2-3% per year (IPCC, 2007). Two important drivers of energy consumption are expected to continue to grow in the future: population is expected to grow towards 9 billion in 2050 and income levels are expected to increase globally by around 3-5% per year (IEA/OECD, 2010). As a result, a further increase in energy consumption is likely. There are several reasons why such energy trends are unsustainable, for instance because of resource depletion, climate change, air pollution and energy security.

The Integrated Model to Assess the Global Environment (IMAGE) was developed to gain more insight and understanding in the complex interrelational global environmental system and the anthropogenic impact on it (MNP, 2006). While it was originally developed as a global single region model, the current version (2.4) is a global 26 region model with comprehensive coverage of direct and indirect pressures on natural systems closely related to anthropogenic energy use, transport, industry, agriculture, housing and forestry. The IMAGE results play a key role in several global studies such as the IPCC Special Report on Emissions Scenarios, the UNEP Third Global Environment Outlook and the Millennium Ecosystem Assessment. It is also used for the fourth Assessment Report of the IPCC.

The IMAGE framework consists of several sub models, The IMage Energy Regional model (TIMER) is the sub-module that aims to describe long-term development pathways in the energy system and is integrated in the IMAGE framework via energy-related emissions of greenhouse gases, air pollutants and land use for bio-energy production. TIMER deals with energy demand and the production of fossil fuels, biofuels, hydrogen and electricity.

So far, offshore wind power was not taken into account in the model. Still, given the vast surface of the sea area and the strong winds, offshore wind represents a large potential source of energy. The world has a large and densely populated coastline area from which offshore wind could be easily accessible. In contrast to onshore wind, offshore wind does not have comparable implementation issues related to not-in-my-backyard points of view. Therefore, offshore wind may hold an interesting promise for future developments of renewable energy. Now with a technological history of about 20 years it has developed an analytical basis from which adequate modelling projections can be made. Additionally, countries around the world have set policies in place to stimulate its development, such as the European Union which has set an ambitious goal of 40GW installed offshore wind capacity in 2020 (EWEA, 2011). More countries have followed, such as the US with a goal of 10GW in 2020 or China with 30GW in 2020 (GWEC, 2011).

These considerations result in the central research question of this thesis: How can offshore wind power be modelled in the IMAGE/TIMER framework and what impact does offshore wind have on the electricity production in case of different scenarios?

In order to come to an answer the following steps were taken, evidently the further outline of this thesis. In chapter 2 the overall dynamics of the IMAGE framework and external driving forces such as population dynamics and economic growth assumptions will be explained. Also the internal dynamics of TIMER are briefly dealt with in chapter 2.3 as a stepping stone to chapter

2.4 about how to model offshore wind. This chapter is explains how offshore wind is embedded in this long-term global multi-technology energy model. Different scenarios are laid out in chapter 2.5 to investigate the impact of offshore wind. Details about data collection will be elaborated in chapter 3. The global offshore wind potential estimations are explained. Costs are estimated using literature on the technological development of offshore wind farms. Also learning-by-doing, depletion and loadfactor data is collected. Chapter 4 shows the impact of offshore wind in case of different scenarios. This is followed by a discussion in chapter 5. Finally, in chapter 6 the conclusions of this thesis are presented, as well as some recommendation for further research.

2 Offshore wind in IMAGE/ TIMER

2.1 Type of model

The IMAGE/TIMER framework is a bottom-up model that models energy technologies that can be used to provide energy services (Van Vuuren, 2009). Substitution is based on relative electricity generation costs differences, which is in turn driven by factors such as technological development. It focuses particularly on the energy systems rather than on the economy as a whole, which is more the approach of a top-down model. A top-down model approach focuses on the economy as a whole, rather than on technology detail and describes substitution across different inputs on the basis of historically calibrated factors. Both approaches have its strengths and weaknesses. A top-down approach resides in a larger economic context and receives many forms of macro-economic feedback. On the other hand, this approach leans heavily on historical behaviour and events, which may not necessarily be relevant for future system developments. A bottom-up approach may lack macro-economic feedback between the energy system and other economic sectors but allows detailed insight in the energy system providing a wide range of policy support. A more detailed explanation of the IMAGE/TIMER framework will be given in the following sections.

2.2 The IMAGE framework

The IMAGE framework is a model that aims to comprehensively describe and understand global environmental change, as well as their causes and feedback mechanisms. It is a helpful tool to investigate the consequences of our actions on the biophysical system and its feedback on the anthropogenic system. The current version, IMAGE 2.4, is a 26 regional model that takes into account regional differences in many of the parameters and assumptions, Figure 1 (Kram & Stehfest, 2006).

Figure 1: Breakdown in regions in IMAGE 2.4 (Kram & Stehfest, 2006).

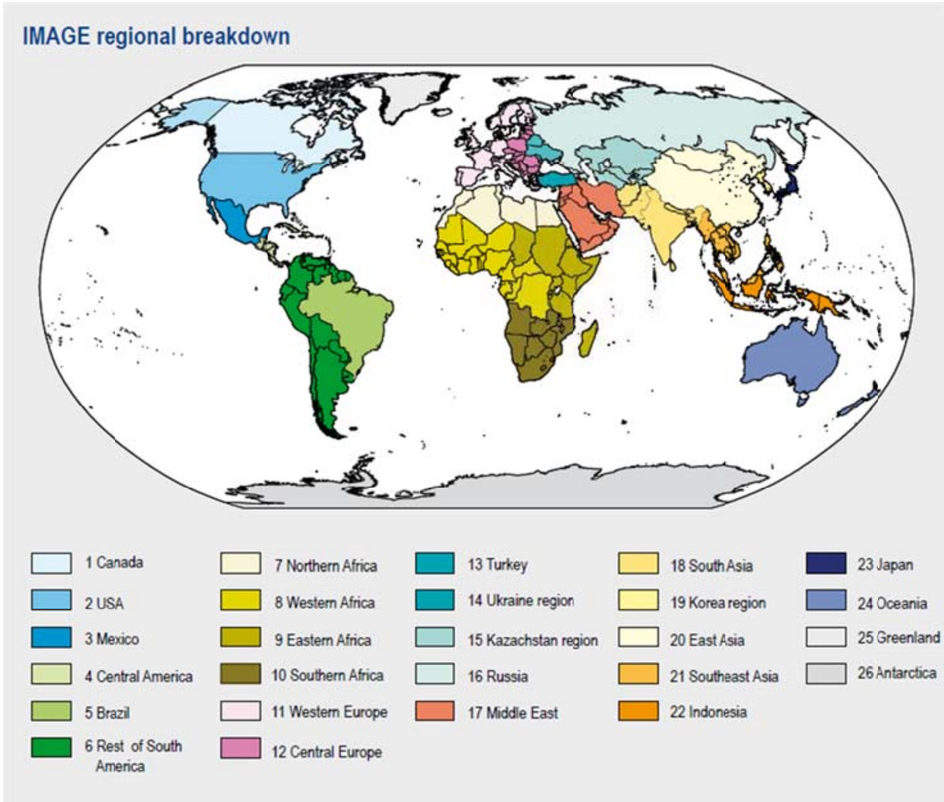
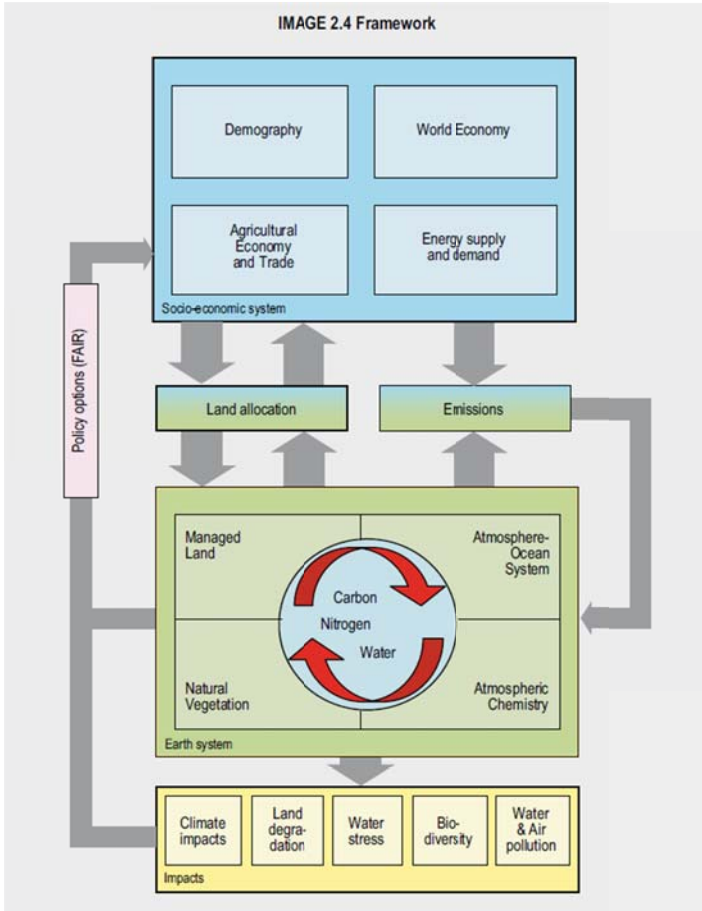


Figure 2 shows the overall outline of the IMAGE 2.4 framework. It shows that the biophysical impacts of the socio-economic system are related via the Earth's system model which interacts with the socio-economic system via land allocation and emissions. Each part of the model briefly dealt with below.

Figure 2: Schematic diagram of IMAGE 2.4 (Kram & Stehfest, 2006).



Demography

Data on population development are taken from authoritative sources like the UN or IIASA. Different assumptions on these projections are made in the Special Report on Emissions Scenarios (SRES). These different "world-views" are also introduced in the IMAGE-framework (Kram & Stehfest, 2006).

Agricultural demand and trade

Demand for agricultural products is projected on the basis of population dynamics and economic developments, called GTAP. This demand is coupled with a global trade analysis model that calculates consumption and trade volumes on the basis of regional and world market prices that are estimated explicitly from production functions. GTAP is coupled with IMAGE which provides land-supply curves, yields and yield changes resulting from climate change and land use changes (Kram & Stehfest, 2006).

Land use and land cover

One of the more notable attributes of the IMAGE framework is the explicit land-use modelling. It takes into account crop cultivation and livestock systems on the basis of agricultural demand as well as for energy crop demand. Spatial proximity to existing agricultural lands or water bodies are used in the rule-based allocation method to estimate crop productivity and land use (Kram & Stehfest, 2006).

Carbon cycle

The carbon cycle model accounts for important feedback mechanisms related to changing climate, CO_2 concentrations and land use. It simulates the geographical terrestrial carbon cycle that is influenced by the land-use and land-cover changes modelled in the previous section (Kram & Stehfest, 2006).

Atmosphere – ocean system

This part of IMAGE determines the composition of the atmosphere on the basis of internal physical conditions in the atmosphere, the ocean, the emissions due to land-use change and the energy system (TIMER) (Kram & Stehfest, 2006).

Climate policy options

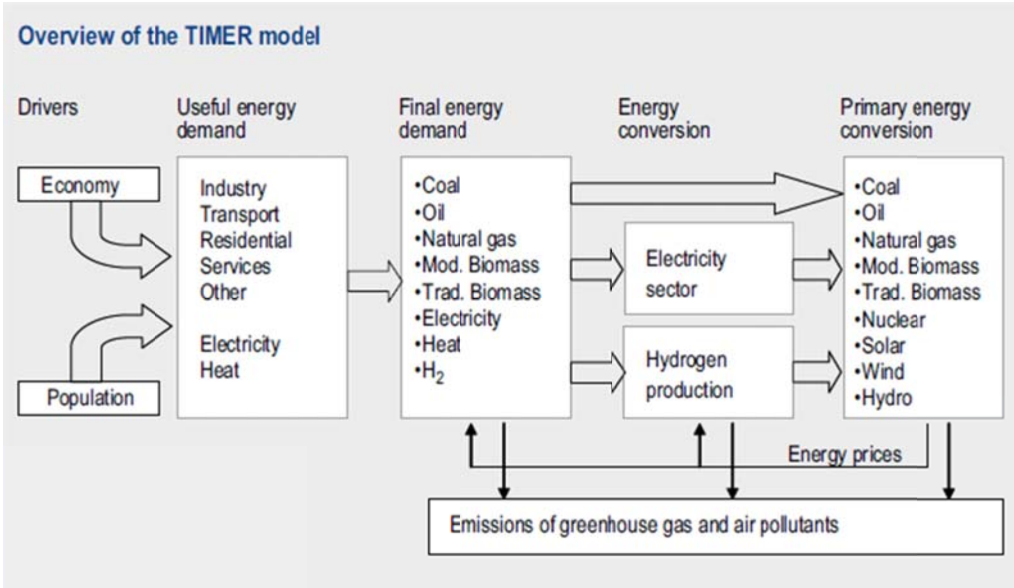
IMAGE results are used for the evaluation of various climate policies. Often, policies are designed and reviewed using the policy decision-support model FAIR. This model is widely used to estimate regional abatement costs for future reductions of greenhouse gas emissions (Kram & Stehfest, 2006).

2.3 TIMER: Energy supply and demand

TIMER is an energy-system simulation model, describing the demand and supply of 12 different energy carriers for 26 world regions, as described by van Vuuren (2006). In the IMAGE framework, TIMER calculates the energy-related greenhouse gas emissions, as well as air pollution emissions and land-use demand for energy crops.

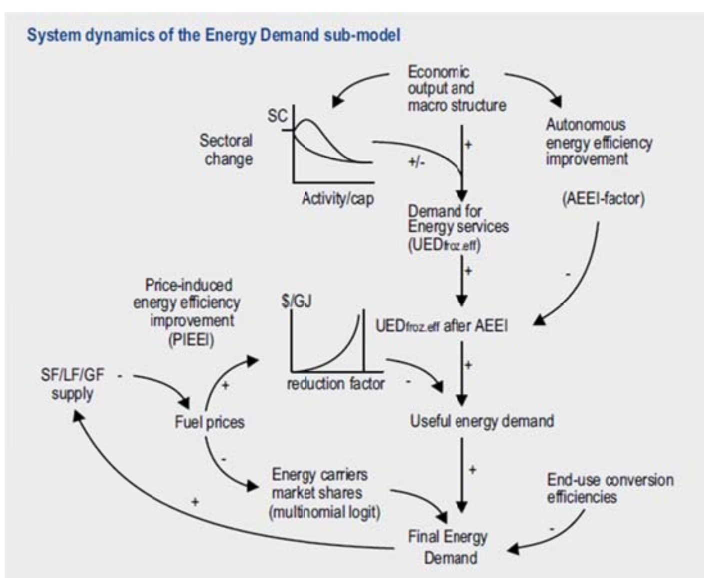
Figure 3 shows an overview of the TIMER model. External drivers such as population and economic developments determine the demand for final energy which is then converted to primary energy via the electricity sector, hydrogen production or other means of conversion. Via specific emission factors per primary energy source the total emissions of greenhouse gas and air pollutants are calculated. Here we briefly discuss how the final energy demand is modelled before we discuss the electricity power generation sub-module (EPG), the most important part with regard to modelling offshore wind power.

Figure 3: Schematic overview of the TIMER model (van Vuuren, et al., 2006)



Final energy demand (see figure Figure 4) is modelled with changes in population and economic activity as the drivers for energy demand. The energy-intensity development (in per capita energy use per monetary unit) is assumed to be a Kuznets curve of the per capita activity level, in the sense that with rising economic activity it first leads to an increase and subsequently to a decrease (van Vuuren et al, 2006). With regard to energy efficiency changes two multipliers play a role (van Vuuren et al, 2006). First, the Autonomous Energy Efficiency Increase (AEEI) multiplier accounts for efficiency improvements that occur as a results of technology improvements of energy conversion technologies independent of prices. Secondly, the price-induced energy efficiency improvement (PIEEI) describes the response in energy use due to consumer behaviour dealing with rising energy costs.

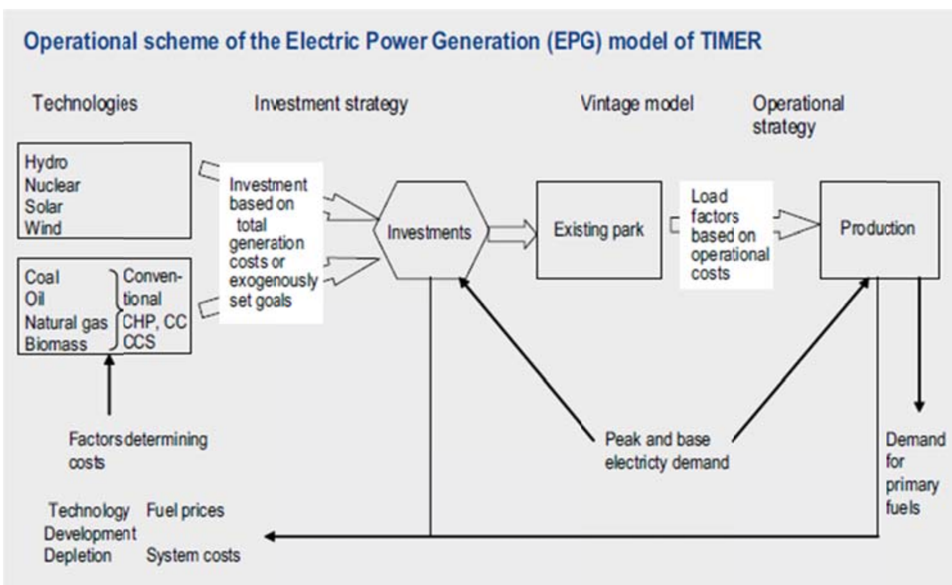
Figure 4: System dynamics of the energy demand model (van Vuuren et al, 2006)



The EPG model (Figure 5) simulates investments in various electricity production technologies in response to electricity demand and to changes in relative generation costs. Different technologies compete for a share in investments based on their total costs. These costs change over the course of time as they are subject to learning-by-doing and depletion effects.

The EPG model describes 20 different fossil fuel (coal, oil and gas) and bioenergy electricity plant combinations (van Vuuren et al, 2006). For each fuel, the model distinguishes a conventional technology, a gasification and combined cycle technology, a combined-heat-and-power (CHP) technology, a carbon-capture and storage (CCS) technology and a CHP technology combined with the CCS technology. Additionally, nuclear power is taken into account as well as three renewable energy sources: solar, onshore wind and hydropower. The renewable energy technologies are modelled similar to other technologies, except for additional costs due to their intermittent character. The additional costs are built up of three different components: first, the additional cost associated with discarded energy if production exceeds demand; secondly, costs associated with back-up capacity if the production is unable to meet demand at certain grid penetration level and, thirdly, costs associated with additional spinning reserve to correct for sudden power drops (Hoogwijk, 2004 p.185).

Figure 5: Schematic overview of the electricity power generation model (van Vuuren et al, 2006)

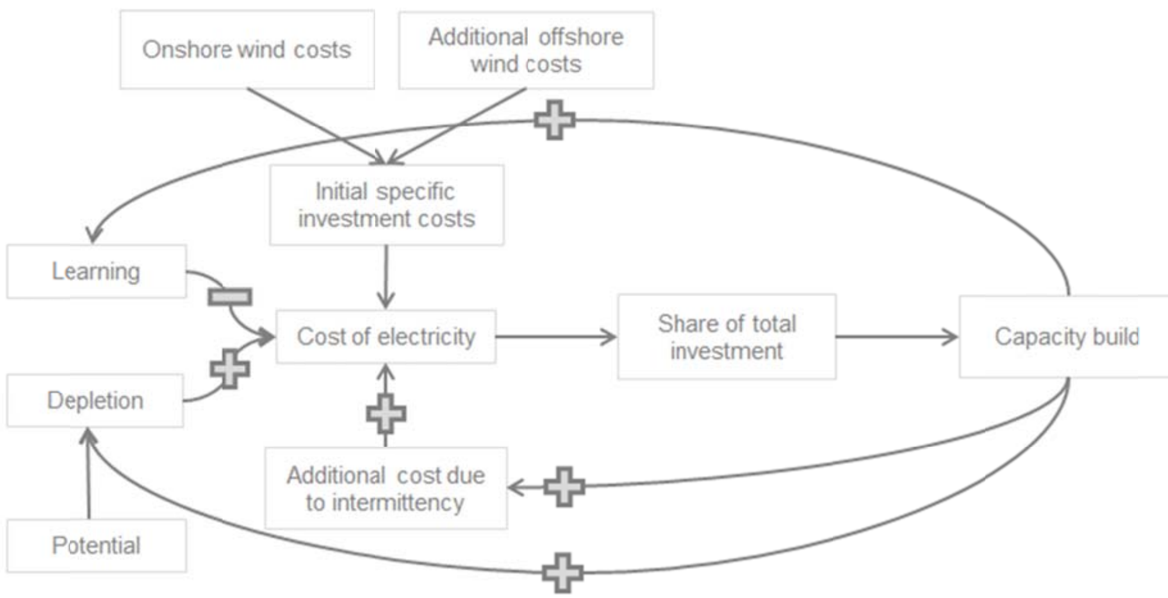


The EPG model contains three renewable energy sources and this thesis aims to add an additional renewable energy technology, offshore wind. Therefore the details of modelling and embedding offshore wind in the IMAGE framework will be further explained.

2.4 Offshore wind model

Figure 6 shows an overview of the offshore wind model as embedded in the TIMER model.

Figure 6: Offshore wind model overview



Details about the data collection and calculations of the costs, potentials and learning curves will be given in the next chapter where all the data assumptions will be fully explained. The following section elaborates on the general dynamics of the offshore wind model.

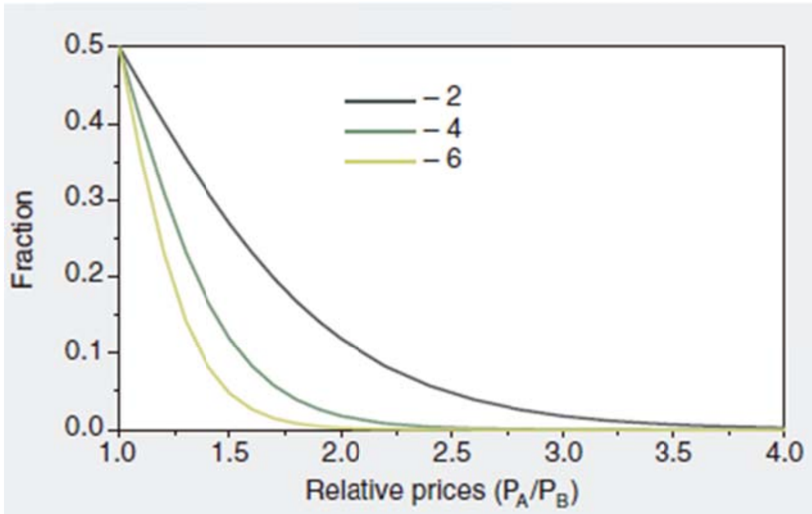
At the heart of the model lays the share of total investment through internal technological competition. The cost of electricity (COE) ($/kWh) per technology determines what market share of the total demand each technology will get. In general, energy technologies that are able to produce electricity at the lowest cost will receive the largest market share. However, technologies never get a full market share as other technologies will always reside in specific niche markets. In order to represent this heterogeneity of the market in the model the investment shares are determined by a multinomial logit function (MNL) (van Vuuren et al, 2007):

Equation 1

$$IMS_i = \frac{\exp(-\lambda c_i)}{\sum_j \exp(-\lambda c_j)}$$

where IMS_i is the share of total investments, c_i the cost or price of production method i and λ the so-called logit parameter, which reflects the sensitivity of markets to relative differences in prices. Essentially it is a cost minimizing algorithm that will provide those technologies that supply the cheapest electricity, with the largest share, however in most cases not a full market share. Figure 7 is a graphical representation of the market share of a technology as a function of the relative price difference with different logit parameters λ.

Figure 7: Multinomial logit equation outcomes for different values of the logit parameter λ (2, 4 and 6) showing the fraction of the market share as a function of the price ratio between technology A and B (van Vuuren, 2007)



The offshore wind industry bears a great deal of similarity with onshore wind industry. Many of its parts, such as the turbine, rotor, tower or nacelle can almost be copied from the onshore wind industry. Some parts require special adaptation of materials, equipment and skills but it is evident that the offshore wind industry is influenced by the developments onshore to a considerable degree. In order to incorporate this notion into the IMAGE framework we have chosen to split up the specific investment costs into two parts. The first part is similar to the cost calculations of onshore wind. The second part consists of the additional costs to place windmills offshore, such as grid connection, offshore installation costs, higher operation and maintenance (O&M) costs or additional turbine costs. This distinction has its effects on the technological learning of the offshore wind technology.

As with solar and onshore wind technology, the more preferable locations will be used first to build offshore wind farms. As the technology expands, wind farms will have to be built further offshore and in deeper waters, driving the price of offshore wind electricity up. This depletion effect is modelled as a dynamic element that receives feedback from the built capacity in the previous years. It indicates additional costs as these locations have less favourable conditions.

On the other hand, businesses and manufactures learn by building new capacity. Incremental improvements, efficiency increase and/or design innovation drive a process described as ‘learning-by-doing’ (Arrow, 1962). These effects tend to drive the price down as more capacity is built and are modelled with the learning curve algorithm:

Equation 2

$$y = \alpha Q^{-\pi}$$

where π is the learning rate, Q the cumulative capacity and α a constant. The learning rate, often indicated as the progress ratio ρ, indicates how fast costs decrease with a doubling of cumulative capacity ($\rho=2^{-\pi}$). As the specific investment costs for offshore wind are modeled into two different parts, the offshore wind technological development deals with two different learning rates. The first part deals with the same learning rate as onshore wind, while the second part deals with offshore specific learning rates, see also chapter 3.3.

A last point of attention is the additional costs that intermittent supply options, such as offshore wind, bring into the system (Hoogwijk, 2004). Three different costs elements have been distinguished:

(1) The need for large investment in back-up capacity due to a low and decreasing capacity credit.

(2) Additional O&M requirement, such as an increase of spinning reserve.

(3) The necessity to discard excess electricity at higher penetration levels.

As more capacity is built, the penetration level increases which induces additional cost to the cost of electricity of offshore wind power.

2.5 Offshore wind scenarios

Three different scenarios are designed to investigate the impact of offshore wind. First a baseline scenario, secondly an offshore policy scenario and thirdly a 2°C climate target scenario. All scenarios will be briefly explained. Table 1 gives an overview of the different scenarios used.

Table 1: Offshore wind scenarios

Offshore wind scenarios		
	No Carbon tax	**With Carbon tax**
Without offshore wind	Baseline	Baseline carbon
With offshore wind	Baseline offshore	Baseline offshore carbon
Policy	Offshore policy	

A first exercise to investigate the impact of offshore wind is to run a baseline scenario with and without offshore wind. This shows how the offshore wind technology will develop by the market without extra measures compared to a situation without offshore wind. The results are presented in chapter 4.1 and discussed in chapter 5.1.1.

A second exercise investigates the impact of offshore specific policy. A scenario is set up given currently known policy goals in several parts of the world in order to investigate how the offshore wind technology develops with extra stimulation measures compared to a scenario without extra policy measures. Several regions have set policy goals in order to stimulate the development of the offshore wind technology. The European Union has set a target to install 40GW in 2020 and 150GW in 2030 (EWEA, 2011). In response to this, the USA designed a policy to install 10 GW in 2020 and 54GW in 2030 (GWEC, 2011). China installed a small wind farm of about 130MW in 2012 in order to learn to achieve 5GW in 2015 and 30GW in 2020 (GWEC, 2011). South-Korea also expressed the wish to participate in the development of the offshore wind industry by setting a policy goal of 2.5GW in 2020 and 23GW in 2030 (GWEC, 2011). The results are presented in chapter 4.2 and discussed in chapter 5.1.2.

A third exercise investigates the impact of the introduction of offshore wind when a 2°C climate policy is set in place through the introduction of a compatible carbon tax path (van Vuuren en de Vries, 2000; IPCC, 2007; den Elzen et al., 2009). The carbon tax adds additional cost on carbon intensive electricity generation technologies in order to stimulate low carbon generation technologies. Figure 8 depicts the course of the carbon price till 2100 leading to a development of the annual CO_2 emissions that is depicted in Figure 9. This carbon tax path leads to a reduction of 83% of the annual CO_2 emissions in 2100. This reduction is achieved by deploying low carbon electricity generation technologies at a large scale. This exercise investigates how the structure of the deployment of low carbon generation technologies changes with the implementation of offshore wind technology. The results are presented in chapter 4.3 and discussed in chapter 5.1.3.

Figure 8: Carbon tax path for 2 °C climate target

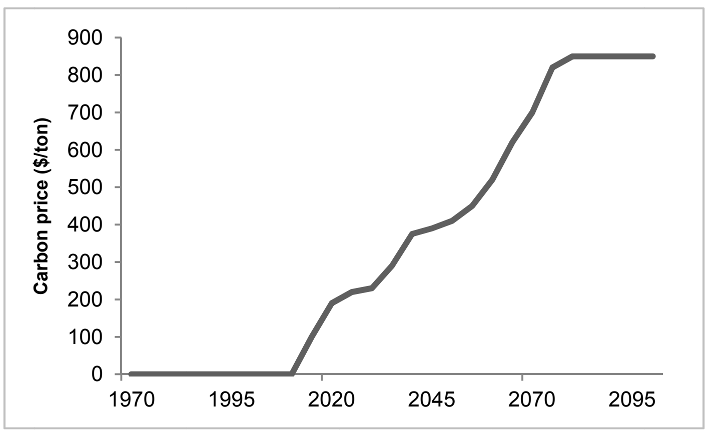
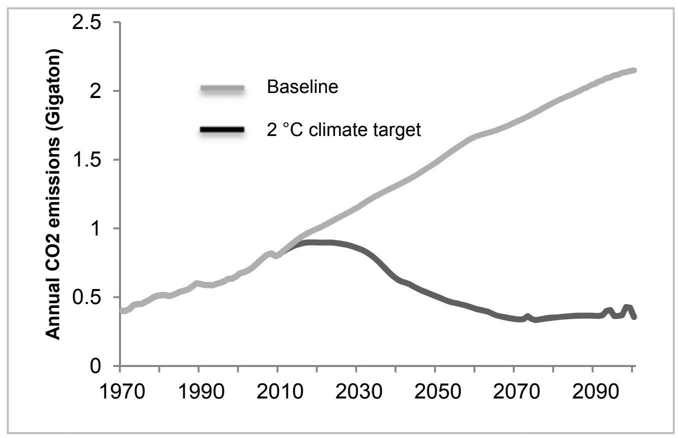


Figure 9: CO_2 emission baseline and 2 °C scenarios



3 Data

The following section elaborates on the details of how the data was collected and constructed. First, the offshore wind potential is explained in section 3.1, after which the costs are explained leading to a specific investment costs and a cost-supply curve in section 3.2. Then, the learning curve and the choice of the progress ratio will be explained in chapter 3.3. Finally loadfactor depletion effects will be explained in chapter 3.4.

3.1 Offshore wind potential

Offshore wind potential has been collected in collaboration with the National Renewable Energy Laboratory (NREL). The following section explains in detail how the offshore wind potential estimations have come to be.

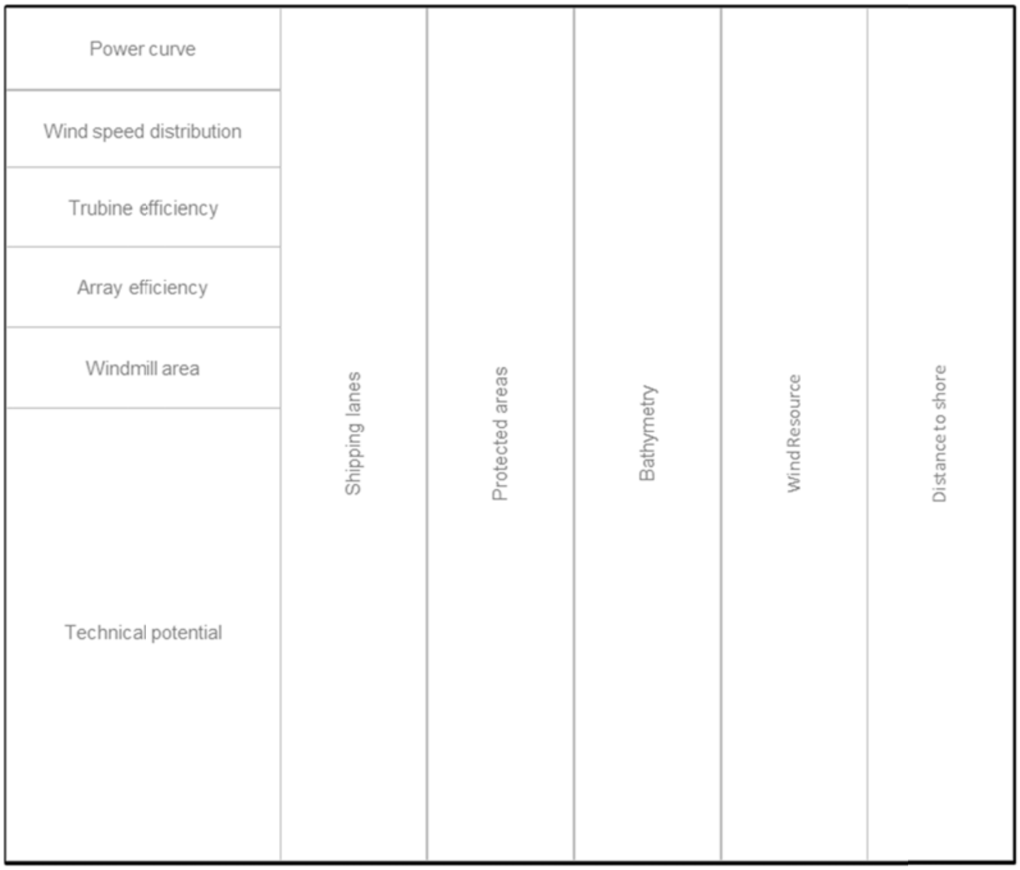
Four levels of offshore wind potential are defined. Each level narrows down the previous level adding constraints and limitations down the road. The first level is the theoretical level which encompasses the total wind energy of the world. The second level is the total area that is available for offshore wind farms, taking into account all sorts of geographical constraints. The third level is the technical potential, adding technological constraints on the geographical potential such as the power density of wind turbines. The fourth level is the technical potential that can be realised economically in the relative framework of other energy technologies (Hoogwijk, 2004).

3.1.1 Theoretical potential

Theoretical potential is the total global energy content of the wind (kWh y^{-1}). This figure is roughly estimated to be around 110 zettajoule (ZJ). This theoretical potential is derived from the theoretical solar energy reaching the atmosphere, where about 2% is converted into wind power on earth (King Hubbert, 1971). Current world energy consumption is about 500 EJ; this means that the total energy potential of wind energy is about 220 times the present world energy consumption.

Figure 10 shows an illustrative representation of the constraints of the theoretical potential leading towards a technical potential of offshore wind per exclusive economic zone (EEZ). The vertical boxes indicate geographical constraints while the horizontal boxes indicate technical constraints. What is left is the geographical potential including the energy losses due to power density, turbine efficiency or otherwise. Note that the size of the boxes is illustrative.

Figure 10: Constraints on theoretical offshore wind power potential



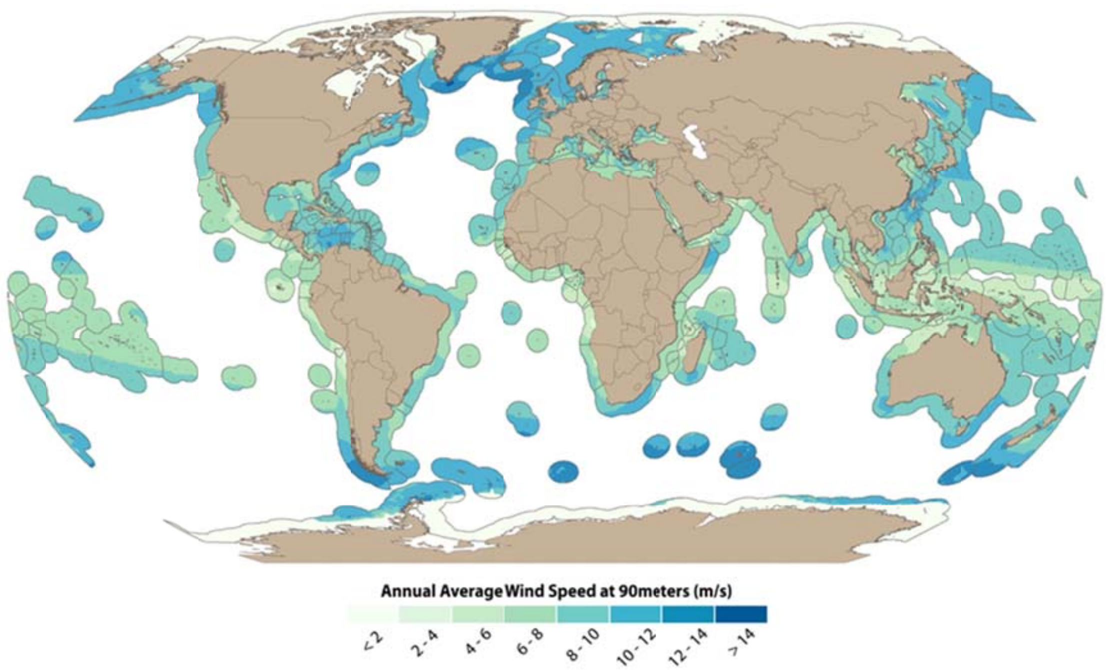
The following sections will explain in more detail how the geographical and technical constraints have come to be.

3.1.2 Geographical potential

The geographical potential data was collected, first by laying out the shorelines to each exclusive economic zone (EEZ). A world map with an offshore bandwidth of a 100 nautical miles (NM) was constructed which was combined with wind speed data taken from the National Oceanic and Atmospheric Administration (NOAA), see Figure 11

.

Figure 11: Wind Speed Map within 200 nautical miles of shore (Zhang et al., 2006)



The NOAA Blended Sea Winds data contained monthly wind speeds on a 30km resolution and a 0.11 wind shear was used to extrapolate to a height of 90m.

A next step was to add bathymetry (underwater depth) data using the NOAA ETOP01 dataset. ETOPO1 is a 1 arc-minute (≈ 1.9 km) global relief model of the Earth's surface that integrates land topography and ocean bathymetry. It is a combined set out of numerous global and regional data sets. On the basis of the area defined in the first part, bathymetry data was added establishing a three dimensional wind potential data set consisting of two distances-to-shore classes, three depth classes and four wind classes.

A final touch was needed in order to correct for offshore areas that are already used for different ends. Protected marine areas and shipping lanes are subtracted of the available geographical area, this data was taken from the National Center for Ecological Analysis and Synthesis (NCEAS).

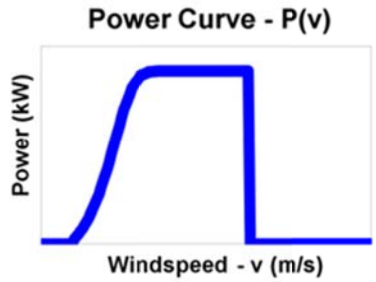
After an assessment of more than 41 million records, a geographical potential in GW per EEZ was established.

3.1.3 Technical potential

In order to come to a geographical potential including the energy losses due to the specific characteristics of wind power technology, a supply algorithm was developed.

A wind turbine is designed to optimally operate at higher wind speeds. This is done because the energy content of the wind is exponentially correlated with wind speeds and wind mills are designed for those wind speeds with high energy content. It is also designed to shut down when wind speeds are too strong, hence the power curve of a wind turbine looks as indicated in Figure 12:

Figure 12: Typical power curve of a wind turbine (Arent et al., 2011)



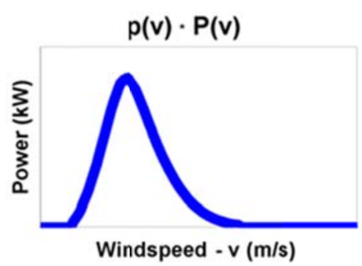
The strength of the wind varies and to take into account the frequency of the wind speeds at any given location, a Weibull distribution function (k) is introduced. With the annual average wind speed known at hub height (calculated using NOAA Blended Sea Winds data with a wind shear of 0.11), we can calculate a power curve that is corrected for the wind speed variation. The correction factor equation using the Weibull distribution looks as follows, which leads to a corrected power curve as depicted in Figure 13.

Equation 3

$$c = \frac{V_{hub}}{\Gamma(1+\frac{1}{k})}$$

where c is the Weibull power curve correction factor, V_{hub} the wind speed at hub height and k the Weibull factor. A value of k=2 is chosen as the most natural wind distribution figure.

Figure 13: Wind speed variation corrected power curve (Arent et al., 2011)



The total potential can now be calculated using a summation of the previously defined power curve and wind speed data combined with several efficiency factors, using the following equation:

Equation 4

$$Potential(MW) = \left(\sum_{v=0}^{V_{max}} p(v)P(v))\right) \cdot \eta_{array} \cdot \eta_{avail} \cdot \eta_{turb}$$

where Potential is the total technical potential of offshore wind in MW, p(v) the wind speed variation distribution power curve, P(v) the wind turbine power curve, η_{array} the efficiency of the wind farm array, η_{avail} the efficiency of the available area (each turbine takes up a certain amount of space) and η_{turb} the efficiency of the wind turbine (NREL offshore wind database, 2011).

3.1.4 Final dataset

The dataset provided offshore wind potentials in MW per EEZ in 24 distinguished categories, as defined by two categories of the distance to shore (0 -50NM and 50 – 100NM), three depth classes (shallow 0-20m, transitional 20-60m and deep 60-200m) and four wind classes (4-7 Beaufort). In order to come to offshore wind potentials in annual kWh, the unit of measure used in TIMER, the following capacity factors were given by NREL:

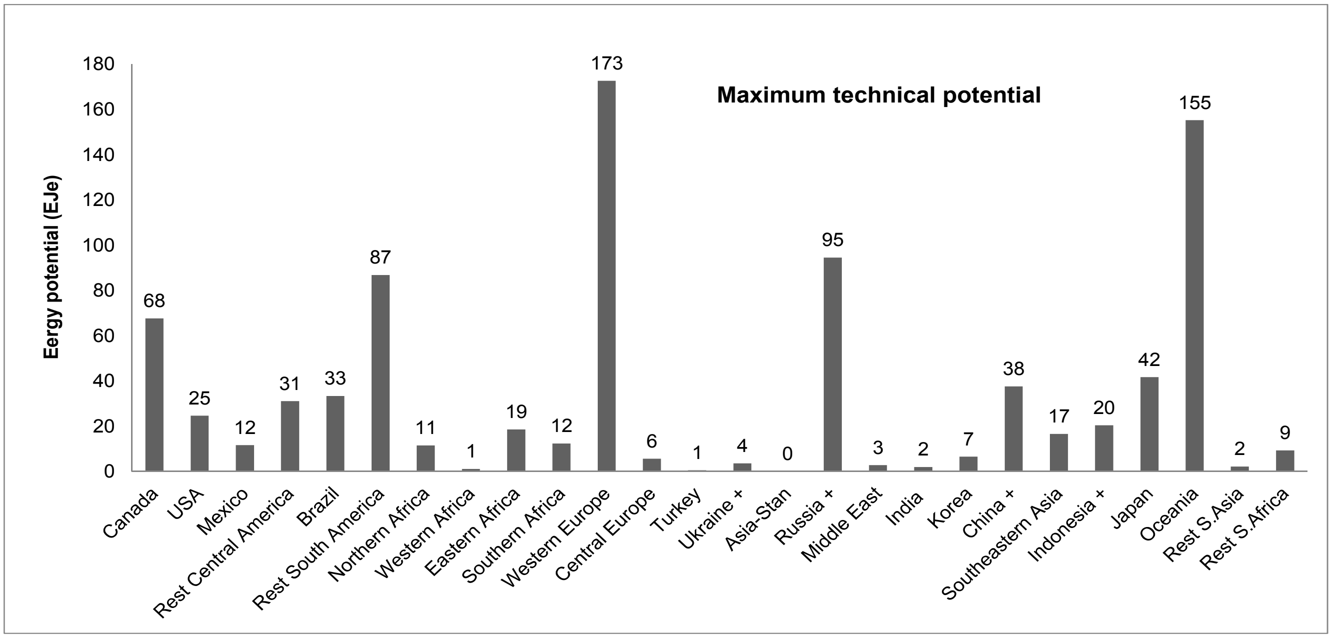
Table 2: Capacity factors (NREL offshore wind database, 2011)

Assumed capacity factors per wind class		
Wind class (Bft)	*Capacity factor NREL*	*Capacity factor chosen*
4	34 – 38%	36%
5	38 – 42%	40%
6	42 – 46%	44%
7	>46%	50%

The capacity factors show a range at different wind classes. Here average values to calculate the annual potential in kWh were taken.

The NREL potentials are allocated to the EEZ's as prescribed by the United Nations Convention on the Law of the Sea. In order to be used in TIMER these potentials are aggregated in the 26 regions of the IMAGE framework (Figure 1). This leads to a maximum technical potential per region as depicted in Figure 14. Areas such as Western-Europe, Oceania and Russia stand out from other regions.

Figure 14: Maximum technical potential per IMAGE region (NREL offshore wind database, 2011).



The regional categorical potentials are further used to calculate a cost-supply curve explained in chapter 3.4.1.

3.2 Costs

This section describes the methodology on how the costs are estimated for the different categories. First, the specific investment costs are calculated for the different depth and distance classes on the basis of data collected from several scientific sources. A regression model is used to extrapolate the empirical findings to the different depth and distance categories. Once the specific investment costs are determined, a cost-supply curve was constructed on the basis of the cost of electricity combining the specific investment costs and the potential data of the previous section.

3.2.1 Cost data

Cost data is collected from Junginger (2008) who published a comprehensive list of all major (projected) wind farm from 1991 – 2012 including the specific investment costs, distances to shore and depths (see APPENDIX I – LIST OF WIND FARMS). In some cases additional figures about depth and distances to shore had to be collected from other sources (4COffshore, 2011). At the time 20 wind farms were in operation, while 8 still had to be build but were able to project the specific investments costs within reasonable accuracy.

3.2.2 Specific investment costs

To come to reasonable cost estimations for the different offshore wind categories, a regression analysis is performed to investigate possible correlations between the specific investment costs and different depths and distances to shore. Each wind farm contains information on the total capacity (MW), depth (m), distance to shore (km) and costs (€/kW). In cases were a range of depth or distance is given, the average is taken for the analysis.

Some outliers have been deleted from the dataset such as some of the very first wind farms built to demonstrate its technical potential. Some have been built so close to shore in such shallow waters that these have been ironically called ‘wet feet windfarms’. These data points introduce noise when estimating the specific investment costs of the commercial wind farm industry. More information on the different development stages of the offshore wind industry can be found in Junginger et al. (2010, p87). Also some of the projected windfarms have been deleted. First of all, offshore wind farm cost projections have been proven to be quite unreliable in the past (Greenacre, 2010). Secondly, some of projected wind farms such as the London Array, a wind farm to be built offshore London, are the first of its kind in terms of size, distance and depth. Taking these arguments in consideration a relative robust correlation (Sig. F. = 0.001, R^2=0.587) was found described by the following model:

Equation 5

$$I_{(€/kW)} = 1326.23 + 7.72 Dis_{shore} + 24.25 Depth + 0.42 Cum_{capacity}$$

where $I_{€/kW}$ is the specific investment cost, Dis_{shore} the distance to shore (km), *Depth* the water depth and $CUM_{capcacity}$ the cumulative capacity. The latter variable had to be taken into account to correct for the learning effects that have taken place.

To control for a situation where the cost of offshore wind technology may indeed not be linear due to e.g. physical engineering limitations of the foundation construction at certain depths, an expert interview was conducted with Jan van der Tempel, Assistant Professor Offshore Engineering at the Technical University (TU) of Delft. Van der Tempel indicates that current engineering techniques are based on monopile constructions, a method similar to offshore drilling techniques. Monopile construction techniques can go up to 140 meters of depth. Only at greater depths completely different techniques and designs have to developed, such as floating constructions. Our dataset comprises depths up to 100 meters and thus there is no immediate argument to suppose the incorrectness of the regression model within the framework of this study.

The NREL dataset contained several ranges with regard to the distance to shore and the depth classes. Table 3 shows the choices that were made taking the average values of all presented ranges.

Table 3: Distance to shore (nautical miles) and depth (meters) assumptions (NREL offshore wind database, 2011)

Distance and Depth assumptions					
	Depth			Distance to shore	
	NREL	Chosen		NREL	Chosen
Shallow	0 - 30	15	Near offshore	0 - 50	25
Transitional	30 - 60	45	Far offshore	50 - 100	75
Deep	60 - 100	80			

The cumulative capacity in 2006 is 816 MW. With the figures given in Table 2 and Table 3 the specific investment costs for all different categories are calculated and presented in Table 4.

Table 4: Specific investment costs for different offshore categories ($2005/kW)

Specific investment cost		
	Near	Far
Shallow	1785	2345
Transitional	2260	2820
Deep	3970	4531

The lowest specific investment cost for offshore wind ($ 1785/kW) is 15% higher compared with onshore wind in the same year. The specific investment costs for conventional coal are $1411/kW, for conventional gas $798/kW and for solar technology $4309/kW. Overall can be said that the costs for offshore wind are still somewhat high compared to other technologies but may in time compete significantly for a market share.

The specific investment costs of offshore wind is modeled so that the additional cost of offshore wind are added to the specific investment cost of onshore wind. The 2005 specific investment costs of offshore wind are 15% higher than the costs of onshore wind. Hence the added costs of offshore wind that are initially implemented in 1971 are 15% of that of the costs of onshore wind in the same year which are $5850/kW. The added costs of offshore wind are therefore $877.50/kW.

3.2.3 The economic potential: cost of electricity

The economic potential is the amount of energy that can be generated at costs that are competitive with other electricity sources (Hoogwijk, 2004). In order to calculate the cost of electricity (COE) we first annuitize the investment costs and divide it by the annual potential:

Equation 6

$$Coe_{cat} = \frac{\gamma \bullet I_{cat} + \varepsilon}{E_{cat}}$$

where Coe_{cat} is the cost of electricity ($/kWh) per category, γ is the annuity factor, ε the cost of operation and maintenance defined as a fraction of the specific investment cost, I_{cat} the specific investment costs per category and E_{cat} the annual potential per category in kWh.

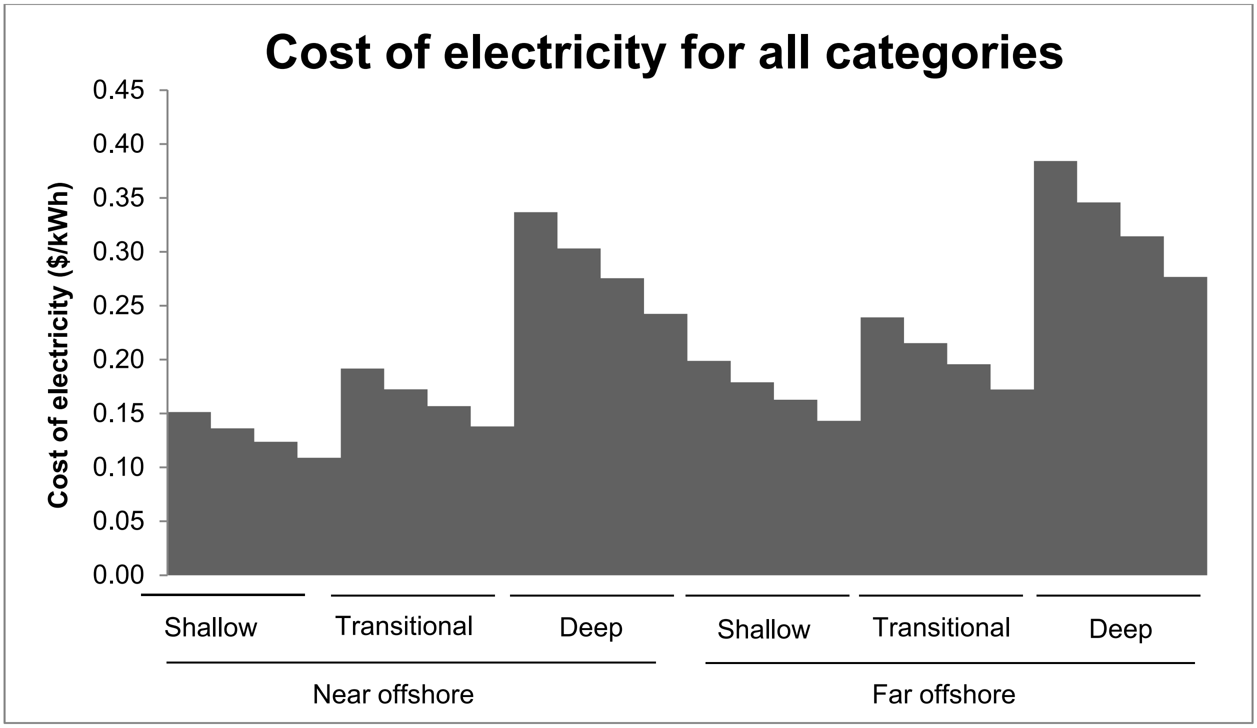
The annuity factor assumes a 10% interest rate and an economic lifetime for a wind farm of 20 years. The O&M costs are taken to be constant and scale-independent at a fixed fraction (0.15) of the capital cost. Literature estimations on the O&M costs differ greatly (Barthelemie, 2001; DEA/CADDET, 2000; Junginger et al, 2010; Kuhn et al. 1998;), an average of the values was taken. As a comparison, onshore wind assumes a 3% O&M cost in TIMER. Table 5 shows an overview of the COE per category and windclass.

Table 5: Cost of electricity for different offshore categories and windclasses (Beaufort) in $ 2005/ kWh

Cost of electricity						
	Near			Far		
	Shallow	Transitional	Deep	Shallow	Transitional	Deep
Windclass 4	0.151	0.192	0.337	0.199	0.239	0.384
Windclass 5	0.136	0.173	0.303	0.179	0.215	0.346
Windclass 6	0.124	0.157	0.276	0.163	0.196	0.314
Windclass 7	0.109	0.138	0.242	0.143	0.172	0.277

Figure 15 shows the COE in a graphical depiction. It shows that there is a rising trend in the COE with increasing depth and distance to shore. The different windclasses with their related capacity factors induce the decline in the COE in each depth/distance class.

Figure 15: Cost of electricity in $2005/kWh for the year 2005 in any given region



It also shows that it may be more cost-effective to build a wind farm far offshore in shallow waters than to build one near offshore in deep waters. The cheapest category to build a wind farm is in shallow waters, near offshore at windclass 7 at the cost of $ 0.109/kWh, slightly higher than the onshore wind costs in 2005 which were around $ 0.093/kWh.

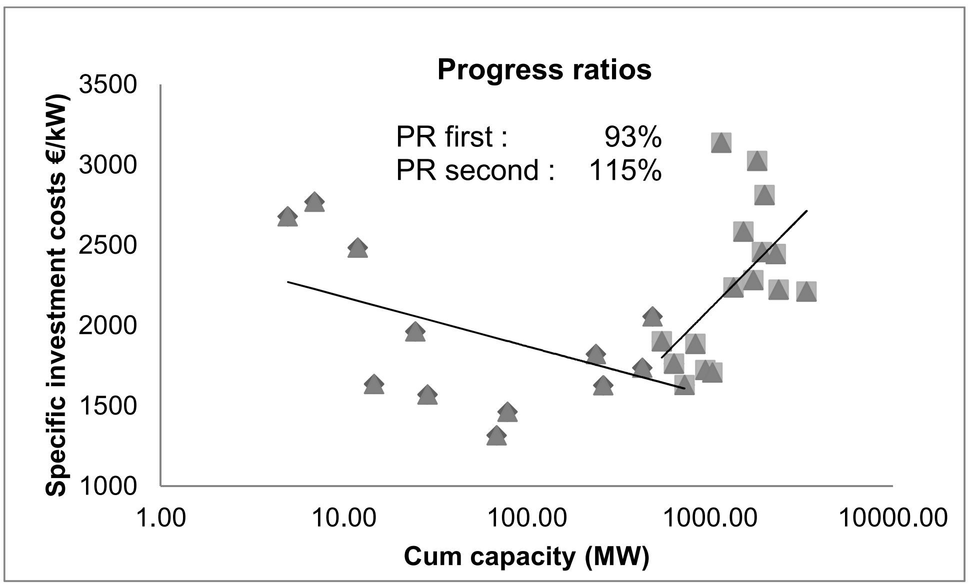
The costs of electricity are used in the so-called cost-supply curve which will be discussed in detail in the chapter 3.4 where the depletion effects will be introduced. In short this cost-supply curve is a ranking of the technical potential in the different categories as defined in previous chapters to the cost of electricity of offshore wind in those categories.

3.3 Learning

Technological learning is the degree to which the producers and consumers increase their technical and economic performance by gaining experience with a technology, a phenomenon called 'learning-by-doing' (Arrow, 1962). This effect is clearly depicted in the experience curve, a figure where the cost of development of a certain product or technology is plotted against the cumulative production on a double logarithmic scale. The result is often a linear curve representing the experience curve (Junginger et al, 2010). Equation 2 shows the formula that is used to estimate the experience curve. The most important element in that equation is the progress-ratio (PR) which indicates the rate at which the costs decline for every doubling of cumulative production. A PR of 80% means that the costs of that specific technology will be 80% of the initial cost after the cumulative production of that technology has doubled.

Offshore wind progress-ratios have been reviewed in various studies (Junginger, 2005; Junginger et al, 2010; Lako, 2002; Isles, 2006; Barthelmie, 2001; CA-OWEE, 2001) and the results vary widely (Figure 16). In the demonstration phase, the so-called 'wet-feet' wind mills were built with a production cost of less than 10€ct/kWh. When the offshore wind farms were built further offshore and in deeper waters, the costs rose up to 15-18 €ct/kWh. Figure 16 depicts the experience curve of offshore wind from 1990 up to 2012 using Junginger's 2010 data. It can be seen that the costs of offshore wind have been decreasing with a PR of 93% up to 2008, after which the costs have been increasing with a PR of 115%. Reasons given for this increase are various (Junginger et al, 2010). First, the wind farms have been built further offshore at increasing depths. Second, the costs of raw material (steel and copper) have increased. Third, the relative small market for offshore wind manufacturers focus particularly on the onshore wind market adding a premium on offshore wind turbines. Fourth, some wind farms experienced severe technical problems in adjusting to the more severe circumstances further offshore. Junginger et al. (2010) states that modest progress ratios of 90-95% can lead to significant cost reductions. This study chooses a progress ratio of 93% for the offshore specific cost reductions.

Figure 16: Experience curve offshore wind 1990 – 2012 (Junginger et al., 2010; See Appendix I)



In chapter 2.4 it was argued that an offshore wind farm actually is an onshore wind farm built offshore. In the light of this argument, the specific investment costs were split into two parts, an onshore and an offshore part. The offshore wind costs profit from both the progress ratio of offshore wind as well as from the onshore progress ratio which is set at 85% in the IMAGE framework (Hoogwijk, 2004; Junginger, 2005).

The equation that is used to calculate the specific investment costs is as follows:

Equation 7

$$SpecCapCost_{offshore} = SpecCapCostIni_{onshore} \bullet LearningEffects_{onshore} + SpecCapCostIni_{offshore} \bullet LearningEffects_{offshore}$$

Where $SpecCapCost_{offshore}$ is the specific investment costs for offshore wind, $SpecCapCostIni_{onshore}$ the initial specific capital cost of onshore wind, $LearningEffects_{onshore}$ the technological learning due to installed capacity and progress ratios of onshore wind, $SpecCapCostIni_{offshore}$ the initial additional specific capital cost to build wind farms offshore and $LearningEffects_{offshore}$ the technological learning due to installed capacity and progress ratios of the offshore specific additional costs. The calculations of the specific capital costs can be found in chapter 3.2.2.

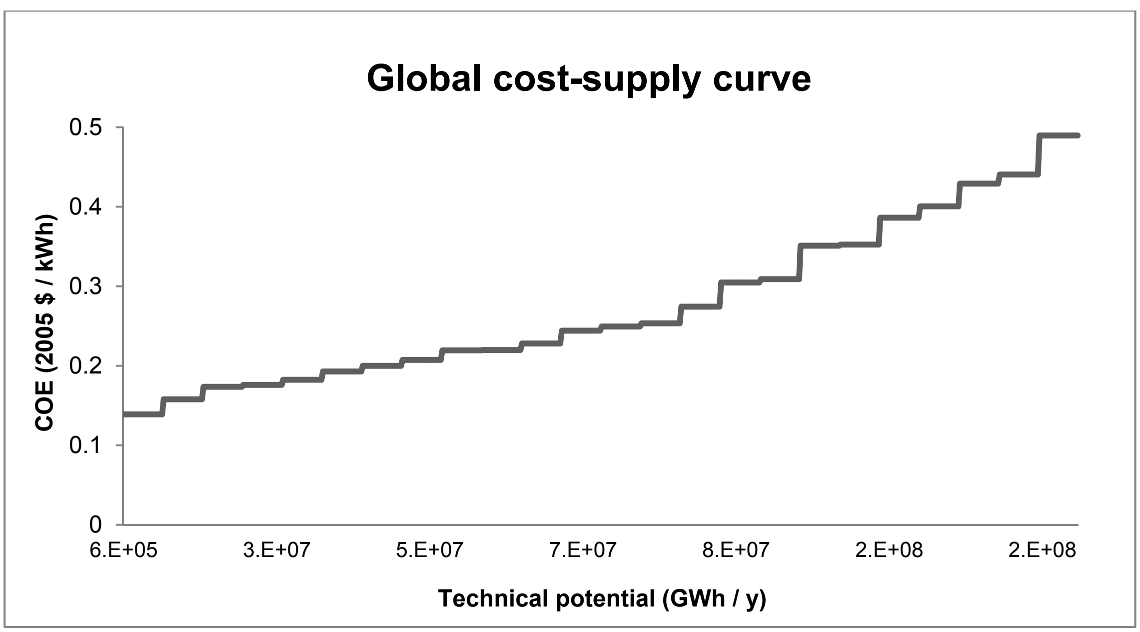
3.4 Depletion

Offshore wind deals with two types of depletion. The first type deals with geographical depletion in the sense that wind farms have to be built on locations that become less favourable as the cumulative production builds up. Wind farms are forced to be built further offshore, in deeper waters with lower wind classes. The second type of depletion deals with a decline in loadfactor which has to be accounted for somewhere else in the system in the form of additional capacity with different technologies.

3.4.1 Geographical depletion

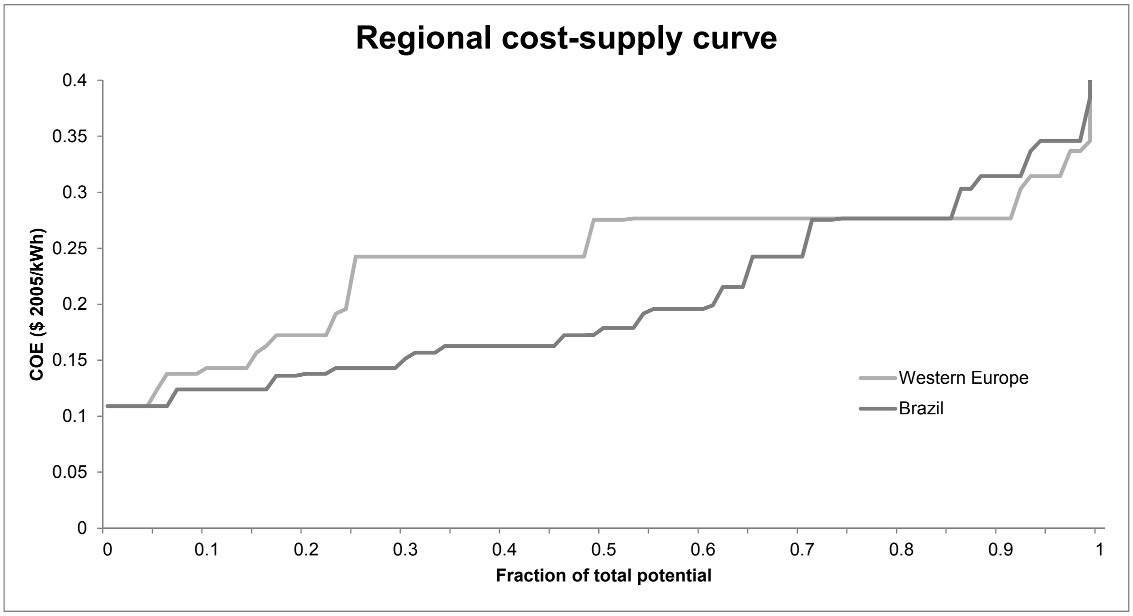
The geographical depletion is introduced in the model in the form of a cost-supply curve. In short this cost-supply curve is a ranking of the technical potential in the different categories to the cost of electricity of offshore wind in those categories. Chapter 3.1 elaborated extensively on the estimations of the offshore wind potential in the world, Chapter 3.2 elaborated on the cost differences with regard to the various properties of the different categories and this chapter will join these two in a cost-supply curve. Figure 17 shows the global cost-supply curve with the cost of electricity plotted to the technical potential.

Figure 17: Global cost-supply curve



Cost-supply curves are implemented regionally and as each region is geographically different, so are the cost-supply curves. Figure 18 shows the regional cost-supply curves of Western-Europe and Brazil, in which the COE is plotted against the fraction of the total potential in that specific region in order to compare the two regions. It can be seen that Brazil has a large part of their offshore wind potentials in relatively favourable locations compared to Western-Europe where the COE is significantly higher in the lower end of the potential range. Note that the total potential of Europe is 11.36TW and Brazil's 2.3TW.

Figure 18: Regional cost-supply curve (Western-Europe and Brazil)



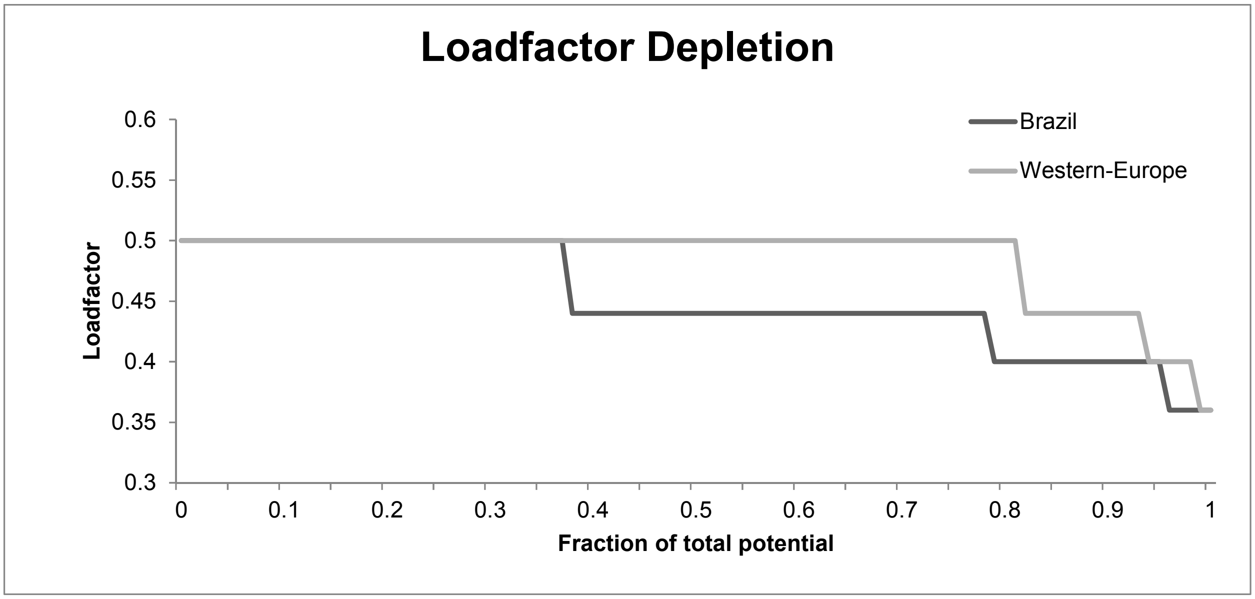
These and 24 other regional cost-supply curves will be implemented in the IMAGE framework so that it becomes possible to assess the global offshore wind potential at a regional level.

3.4.2 Load factor depletion

A second form of depletion is the loadfactor depletion. As offshore wind farms are forced to be built on less favourable locations, the loadfactor for the wind farms will decline simultaneously. When the loadfactor of an intermittent energy supply technology drops, a correction somewhere else in the system must be made such as additional back-up capacity or extra spinning reserve (see chapter 2.4).

Figure 19 shows the loadfactor decline curve as a fraction of the total potential for two regions, Western-Europe and Brazil. Regional differences are clearly present as Western-Europe has a large part of their potentials at a steady high loadfactor of 0.5, whereas Brazil suffers a decline to a loadfactor of 0.44 after a third of its potential is exhausted.

Figure 19: Regional loadfactor depletion



These regional loadfactor decline curves will be implemented in the IMAGE framework in order to be able to correct for loadfactor decline at regional level.

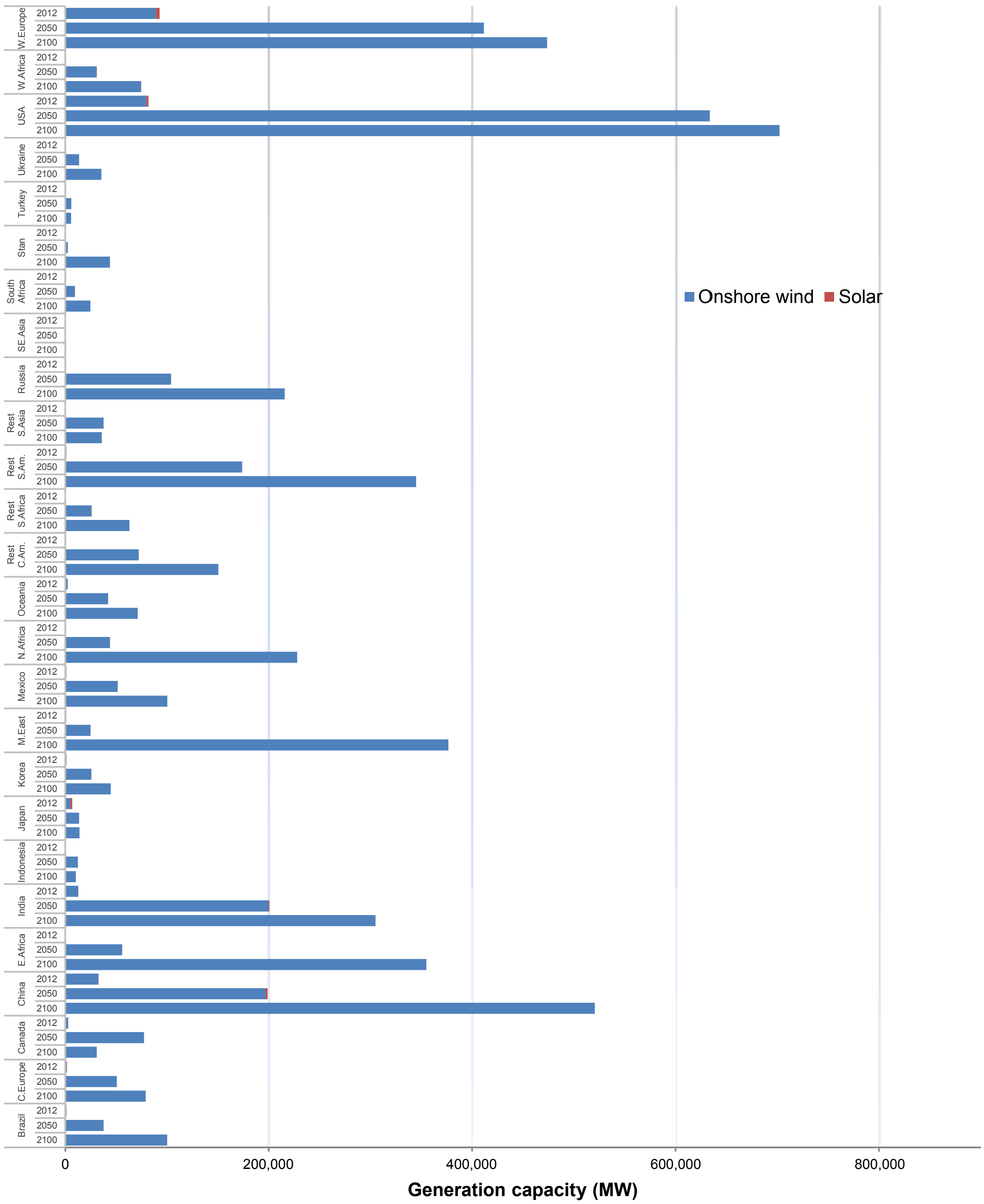
4 Results

The first scenario investigates the impact of offshore wind by producing baseline modelling results with and without offshore wind. A second set of scenarios investigates the impact of offshore policy goals. A third scenario investigates the impact of offshore wind in a 2°C climate target scenario.

4.1 With and without offshore wind baseline scenarios

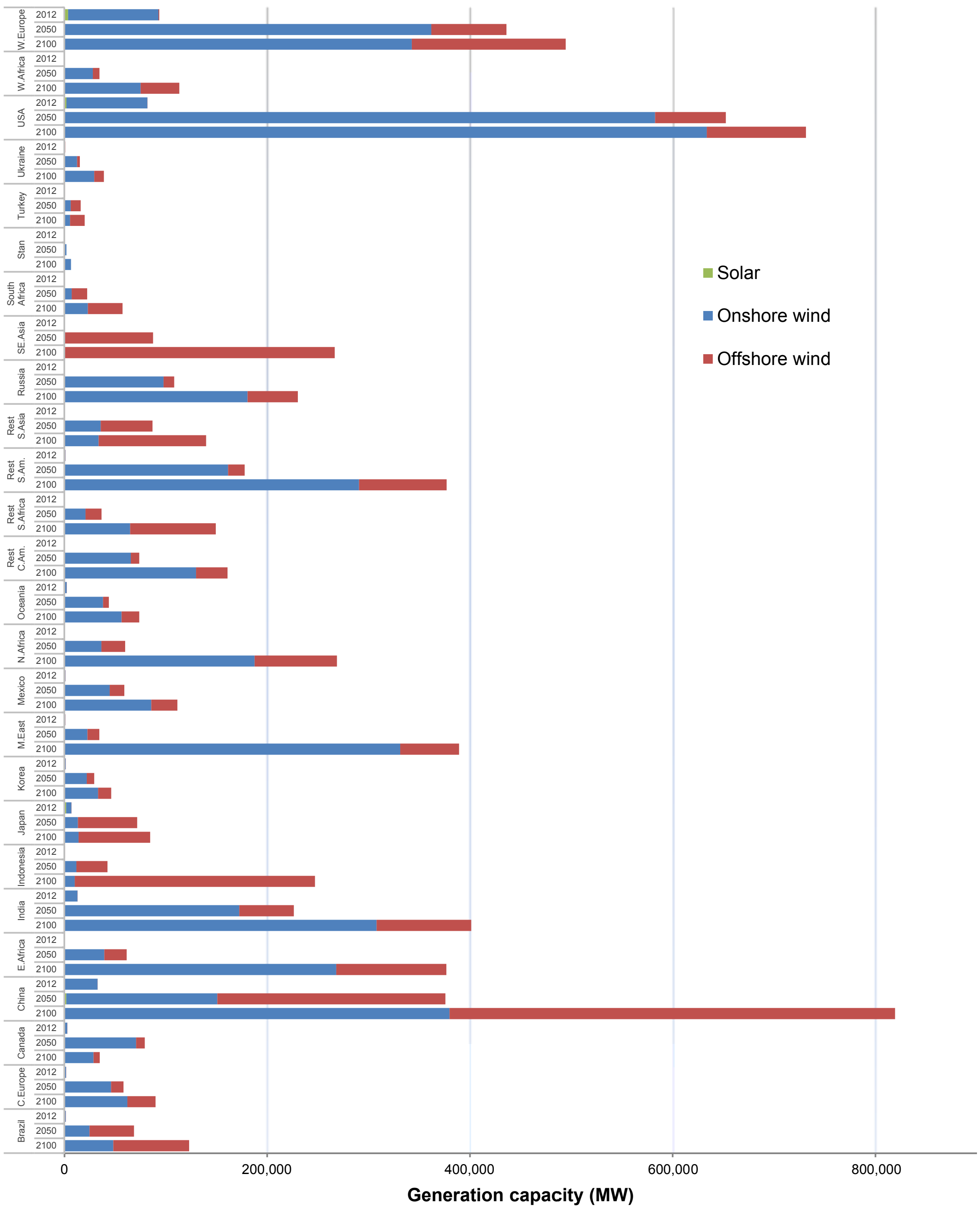
Figure 20 and Figure 21 shows the impact of offshore wind in terms of installed generation capacity in all regions at three different time periods in a baseline scenario. Figure 22 shows the impact of offshore wind in terms of the global renewable electricity production share. The impact is also reflected in the total global annual CO_2 emissions in Figure 23. Finally, offshore price development relative to other technologies is depicted in Figure 24.

Figure 20: Regional renewable generation capacity without offshore wind



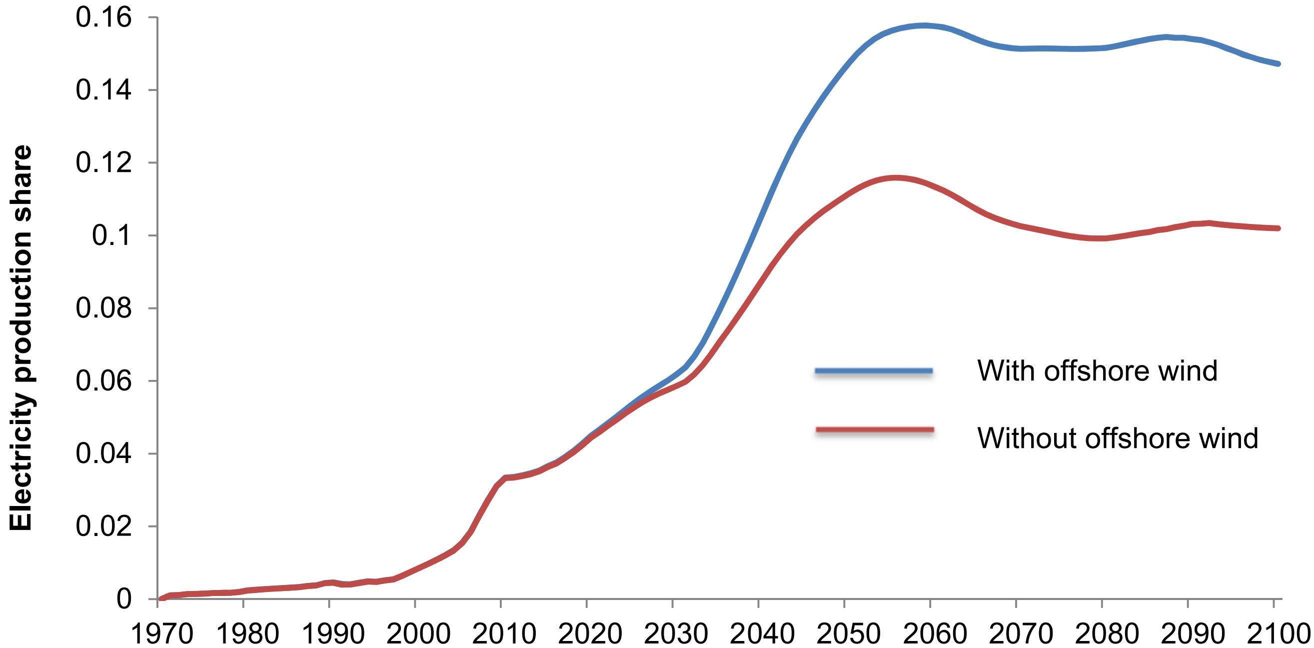
The global renewable generation capacity in 2100 with solar and onshore wind but without offshore wind is projected to be 4.406 GW. The majority of this capacity is produced by onshore wind technology as solar energy remains uncompetitive compared to other electricity generation technologies (Figure 24). Regions that will account for a significant share of the renewable generation capacity are Western Europe, the USA and China.

Figure 21: renewable generation capacity with offshore wind



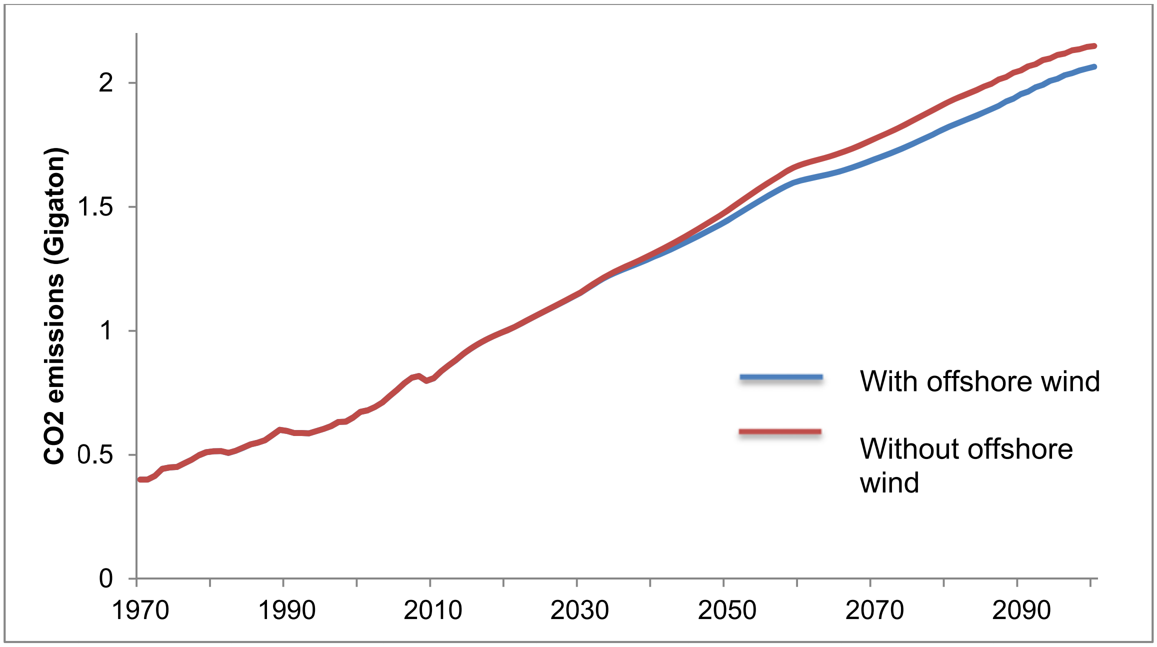
The global renewable generation capacity in 2100 with solar, onshore and offshore wind included is projected to be 5.851 GW: an additional 1.445 GW of additional renewable electricity generation capacity compared with the scenario that excluded offshore wind technology. Regions that will account for a significant share in the offshore wind capacity are China, Western Europe, USA, Southeastern Asia and Indonesia.

Figure 22: Global renewable electricity production share with and without offshore wind



The additionally installed capacity due to offshore wind can also clearly be seen in the renewable electricity production share. Figure 22 shows the global renewable electricity production share from 1970 to 2100 with and without offshore wind technology. The addition of offshore wind technology projects a 44% increase of the global renewable electricity production share. In the scenario without offshore wind 100% of the renewable share is taken up by onshore wind. In the scenario with offshore wind this is reduced to 62%, while offshore wind takes up 38%.

Figure 23: Global total annual CO2 emissions with and without offshore wind



The increase of the global renewable electricity share is also reflected in a reduction of the total annual global CO_2 emissions (Figure 23). Global annual CO_2 emissions decrease with 84 Megaton in 2100 due to the implementation of offshore wind technology, a 4% decrease as compared with scenarios that exclude offshore wind technology.

Figure 24: Price per kWh developments in $ 2005 of various electricity generation technologies

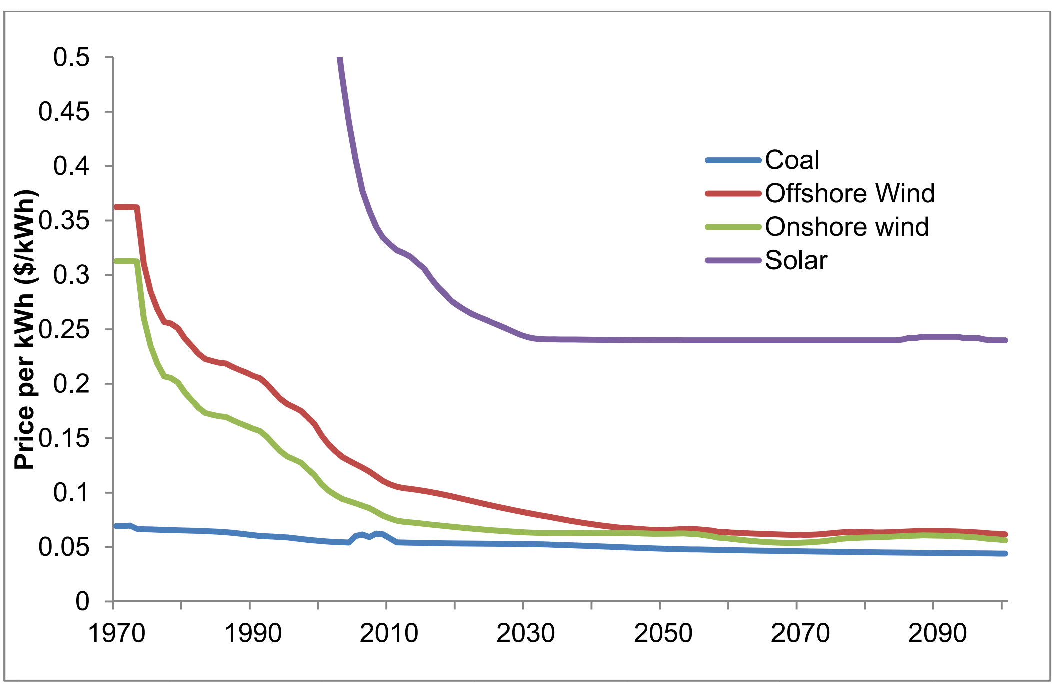


Figure 24 shows the relative contribution of offshore wind, by showing the price per kWh developments from 1970 to 2100 in comparison with other electricity generation technologies. In

2012, the offshore COE is $10.4ct. Compared with e.g. the 2012 COE of coal ($5.4ct) or onshore wind ($7.3ct) the COE of offshore wind steadily moves towards a competitive level.

4.2 Offshore wind policy scenario

The policy goals described in chapter 2.5 have been implemented in TIMER to investigate the impact on the price and generation capacity of offshore wind technology. Figure 25 shows the price development of offshore wind of the policy scenario compared with the baseline scenario. In 2020 the price of offshore wind in the policy scenario is $8.8ct, while the price of offshore wind in the baseline scenario is $9.5ct.

Figure 25: Offshore cost of electricity development under policy scenario & baseline scenario

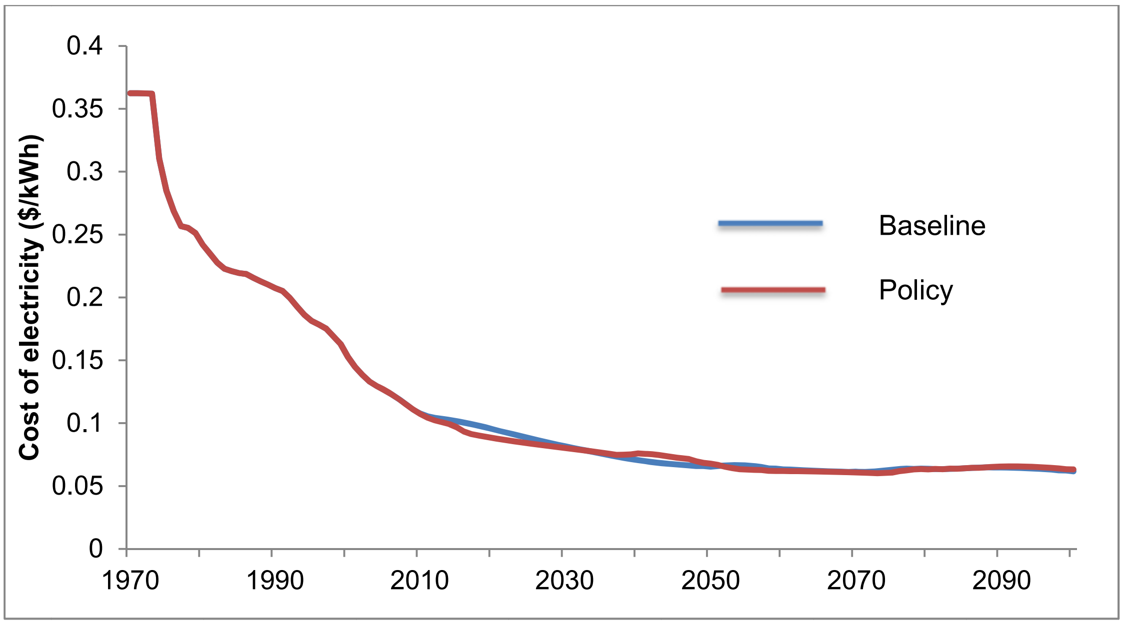
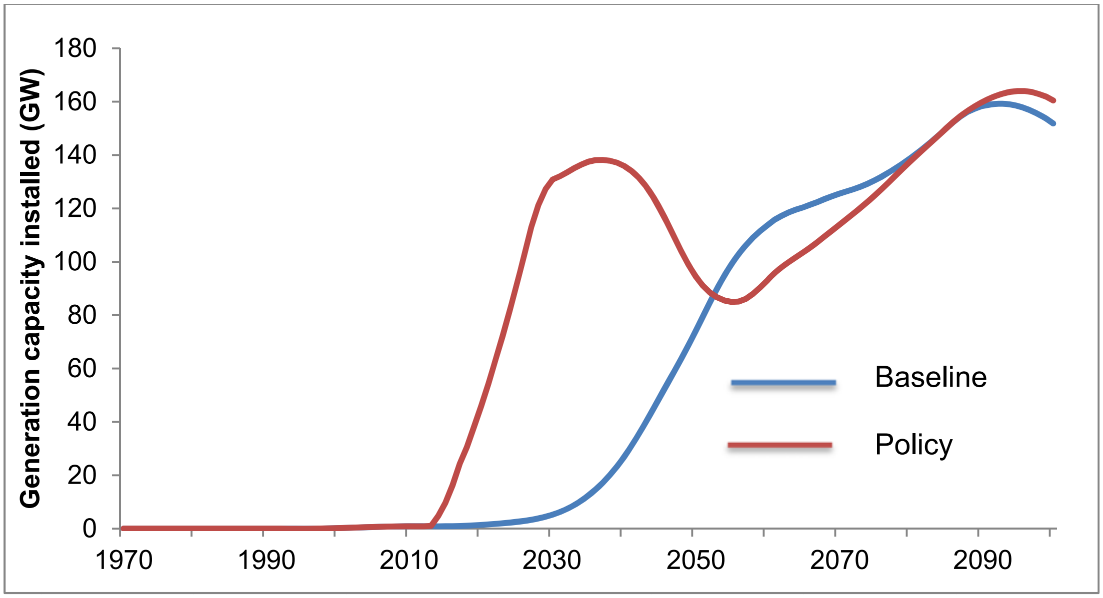


Figure 26 shows the development of installed capacity of offshore wind for the policy and baseline scenario from the period 1970 to 2100. The strong increase of offshore wind capacity in the period 2012-2030 clearly represents the policy goals as described in chapter 2.5. The offshore wind capacity in 2030 reaches 130GW, while the baseline scenario reaches 5.2GW.

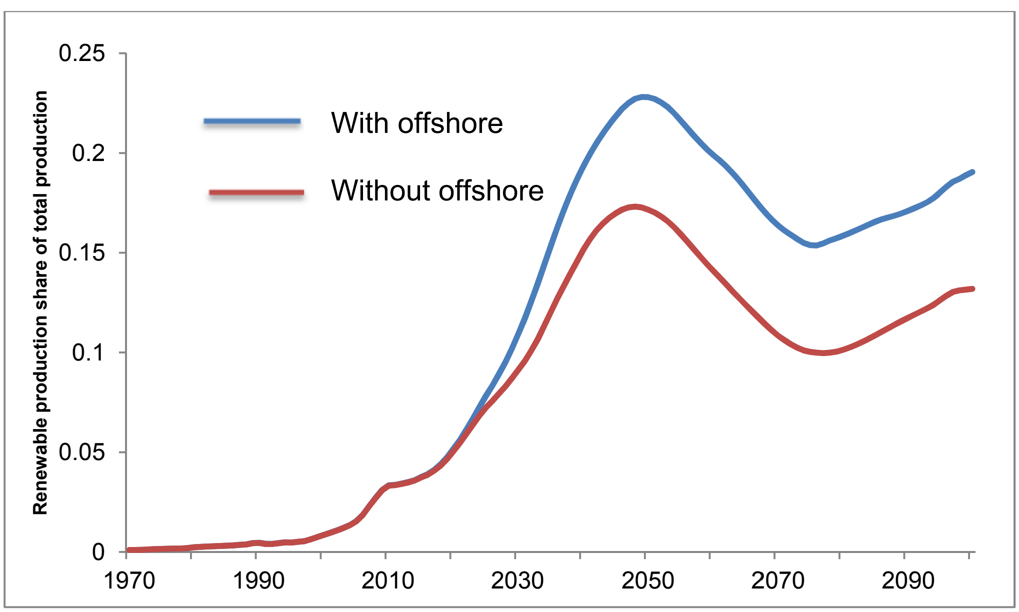
Figure 26: Development of installed generation capacity for Western Europe according to policy goals in GW.



4.3 2°C carbon tax scenario

In a 2°C carbon tax scenario with offshore wind the total renewable production share rises to 19% compared to 15% in a baseline scenario with offshore wind. Figure 27 shows that the implementation of offshore wind induces a 44% increase of the share of renewable energy production in the system. The generation capacity of onshore wind declines from 700 GW to 460 GW in 2100. Also the generation capacity of nuclear declines from 100GW to 55GW, while the natural gas carbon storage technology increases with 40GW. Offshore wind capacity takes up 250GW in 2100, 35% of the renewable generation capacity.

Figure 27: Renewable production share of total production with and without offshore wind in a 2 °C climate target scenario



5 Discussion

5.1 Scenario results

The following sections discuss the results presented in chapter 4.

5.1.1 With and without offshore wind baseline scenarios

Figure 20 and Figure 21 shows the impact of offshore wind in terms of installed generation capacity in all regions at three different time periods. Interestingly, regions such as Southeastern Asia or Indonesia, which initially hardly played a role in the global renewable generation capacity become a significant player when offshore wind technology is included. These regions possess a large potential of cost effective offshore wind potential compared to other renewable electricity generation technologies (Figure 14).

The added energy potential of offshore wind power at relatively competitive prices induces a 44% increase of the global renewable electricity production share in 2100, as depicted in Figure 22. In the scenario without offshore wind 100% of the renewable production share is produced by onshore wind. In the scenario with offshore wind this is reduced to 62%, while offshore wind produces 38%. The increase of the global renewable electricity share is also reflected in a reduction of the total annual global CO_2 emissions by a 4% decrease in 2100 (Figure 23). Evidently this is because offshore wind is a zero emission electricity generation technology.

Figure 24 shows the price developments from 1970 to 2100 in comparison with other electricity generation technologies. The decline in price in the period from 1970 to 1990 may be explained by the association with the onshore wind industry developments. This period shows a strong decline even though no offshore wind capacity was built in that period. Also can be seen that the offshore wind price departs from the onshore wind price because the learning effects on the offshore part only come into play from 1990 onwards when the first offshore wind farms are installed. In 2012, the offshore wind COE of $10.4ct steadily moves towards a competitive level. This COE is a value that induces a certain market share even though the price is not directly competitive with other generation technologies. Reasons for this induced market share are given in chapter 2.4 where the functioning of the multinomial logit function is explained. This relatively small but crucial market share in combination with the on-going onshore wind developments drive the cost of electricity down to $6.5ct in 2050 with a further decline to $6.2ct in 2100.

5.1.2 Offshore wind policy scenarios

Figure 25 shows the price development of offshore wind of the policy scenario compared with the baseline scenario. The figure shows that the COE decreases slightly faster in the policy scenario compared with the baseline scenario. This is because, as more capacity is installed, more learning effects come into play driving the price of offshore wind generated electricity down. But as a significant part of the costs of offshore wind depend on the development of onshore wind, the price decrease is relatively modest. Also note that the price of offshore wind increases slightly after 2030 in the policy scenario. This is because the implemented policy goals reach till 2030; after this period the model calculates that there is an abundance of offshore wind capacity deciding to wait to build additional capacity driving the price up. A period later, when existing offshore wind capacity decays and electricity demand increases, more offshore wind capacity is installed after which the price development recovers, this is clearly illustrated in Figure 26.

Additionally, an advanced offshore policy scenario was exercised to investigate offshore price developments under extreme policy circumstances. The scenario simulated a global agreement on the development of the offshore wind technology. Each region in the world designs policy to take up the same fraction of their offshore wind potentials as the current front runner, the policy target of Western Europe. The target is to install 150 GW of offshore wind power in 2030, this is 0.013% of the total regional offshore wind potential. All other regions employ this target and agree that this level of capacity will at least be maintained for the future. Some regions however have such a vast amount of potential that even this small fraction outnumbers their total generation capacity in 2030, therefore a cap of a maximum of 20% offshore wind is placed on each region. The results showed only minor price improvements as was the case with the previously explained offshore policy scenario. Mostly this is because the developments of the offshore wind industry are modelled in such a way that the price developments are influenced by the onshore wind industry for 85%. The onshore wind industry is more mature and further down the learning curve showing relatively minor learning feedback effects. Additionally, the offshore progress ratio is relatively high (PR=93%) and when the offshore industry matures the price decrease will be modest likewise.

5.1.3 2°C climate target scenario

Similar to the baseline scenarios, the inclusion of offshore wind induces a 44% higher share of renewable electricity production (Figure 27) in a 2°C climate target scenario. Interestingly, the composition of electricity generation technologies changes quite significantly. The generation capacity of onshore wind declines from 700 GW to 460 GW in 2100 and the generation capacity of nuclear declines from 100GW to 55GW. This may be explained because of an increased level of internal competition between low carbon electricity generation technologies due to the introduction of offshore wind. The capacity of natural gas carbon storage technology increases with 40GW to compensate for the loadfactor decline due to extra installed capacity of intermittent supply technologies.

The absolute emissions as shown in Figure 9 do not change with the implementation of offshore wind in the carbon tax scenario. The introduction of the carbon tax pushes carbon intensive generation technologies out of the market and seeks for an optimal alternative route. This route consists of installing less onshore wind and nuclear capacity but hardly influences the carbon technologies, the increase in natural gas with carbon storage as a small exception. Hence the absence of change of carbon emissions with the introduction of offshore wind technology.

5.2 Theoretical discussion and implications

The addition of generation technologies can introduce significant changes in the outcomes of the TIMER model. The introduction of offshore wind changed the composition of the electricity generation mix considerably. The results of this study indicate the necessity for a continued expansion of TIMER and other global environmental change models.

The introduction of more intermittent supply options may present difficulties in terms of penetration levels in the energy system. TIMER takes into account the mismatch between electricity demand and supply resulting in excess electricity that either needs to be stored or discarded. Hoogwijk (2004) estimated that this ought to happen at a 20% penetration of intermittent supply options. At 30% penetration this effect is the most significant factor for cost increase. At a 2 °C climate policy scenario with offshore wind, renewables take up 23% at some point in time. Adding more intermittent supply options might cause a renewable market share ceiling due to additional costs driven by increasing penetration levels.

A related but different development should also be something to follow closely. Recent developments in Germany indicate that grid connectivity with mountainous regions with hydro power storage capacity may play an important role to store excess electricity in the future (Auer, 2012). Alpine and Scandinavian countries have set ambitious goals towards installing additional water storage capacity. These developments will have several effects in the model in terms of curtailment and back-up capacity.

The costs and learning effects of offshore wind are coupled with developments of the onshore wind industry, however the offshore wind capacity developments are not coupled with the cost and learning effect of the onshore wind industry. A sensitivity exercise was performed to investigate the cost development of onshore wind with and without offshore wind. The results show a 2.2% increase of the specific capital cost of onshore wind with offshore wind in 2050 and a 3.4% increase in 2100. This increase in price is due to the introduction of offshore wind that mutually compete for a market share which results in a 900 GW capacity decrease for onshore wind. The additional installed offshore capacity is not taken into account in learning effects for onshore wind. Though the results of this sensitivity exercise show minor effects, this should be a point of interest for further model improvement.

Recent studies indicate that global wind potential estimations can be significantly improved by increasing the resolution of the grid cell maps to estimate the energy potential (Badger et al, 2010). Current onshore wind potentials in TIMER are estimated on the basis of 0.5°x0.5° (50x50km) grid cell maps (Hoogwijk, 2004) and offshore wind potential on the basis of 30x30km grid cell maps. Badger et al. (2010) have found that the estimated mean power density of a 50x50km cell is almost half compared the mean power density of a 0.1x0.1km cell. These results indicate that improved on- and offshore wind potentials will have significant impact on current on- and offshore wind modelling results.

A point of interest that came forward in the interview with J. van der Tempel, Assistant Professor Offshore Engineering at the TU Delft, is the inclusion of economic, infrastructure and political parameters. The offshore wind industry is rather capital intensive and a secure investment climate with a stable political situation may be of influence. Also offshore grid connection may pose severe problems in underdeveloped areas. Western Europe has a rather safe investment climate with a well-connected and maintained electricity grid but regions such as Southeast Asia or Indonesia that are projected to install large amounts of offshore capacity may not meet the investment standards required.

As already discussed in chapter 3.3 the estimation of offshore wind learning rates is difficult and the data shows a diffuse pattern. Several reasons are already given and explained in literature (Junginger et al, 2010). However an additional point of interest to further improve the learning rate projections might be to correct for depth and distance. Chapter 3.2.2 describes a correlation found between the specific investment costs at various depths and distances. An interesting exercise would be to adjust the specific investment costs of the various wind farms corrected for these influences and re-investigate the learning rates.

The inclusion of offshore wind pushed a significant part of onshore wind capacity out of modelling projections. In the baseline scenario with offshore wind the total onshore wind capacity declines with 777GW as compared with the baseline scenario without offshore wind. The onshore wind industry copes with increasing social resistance in further expansion. The inclusion of offshore wind in the model might bring the modelling projections to more realistic figures.

A comparison of the IMAGE/TIMER offshore wind model as described in this study with other modeling projections is highly desired. However no other studies describing modeling offshore wind in global environmental change models was found. A comparison study as soon as other scholars publish results is one of the more imminent steps forward.

5.3 Practical implications

The modeling results show that offshore wind will reside in a competitive area in the near term future. The baseline offshore scenario shows that the offshore starts to take significant market share from 2030 onwards without additional policy measures profiting from the ongoing onshore wind developments. The offshore policy scenario, where the current policy goals of the EU, USA, South Korea and China have been investigated, showed only modest price improvements indicating a relatively minor impact. This notion is backed by the modeling results in an advanced policy scenario, also showing minor price improvements.

Overall, the results of this study indicate that offshore wind may play an important role in the development of renewable energy. Three important aspects of the offshore wind industry make it a technological development to notice. First the offshore wind industry bears great similarity with the onshore wind industry which makes the development of this technology a logical and relatively easy step. Also crossover learning effects take place from which both industries will profit. A second aspect , which is not taken into account in these modeling results, are the not-in-my-backyard issue. The onshore wind industry deals with significant lag because of social resistance in further expansion. Offshore wind on the contrary will not face these issues and will be able to grow unbridled. A third aspect is the current policy developments in several parts of the world to actively stimulate the offshore wind industry. Although modeling results show minor improvements in future offshore price developments when specific policy targets are implemented, it has to be noted that the policy measures of the past ten years are the prime driver for the costs to drop to present levels. Another trend that might take place is that governmental wind policy measures will shift from onshore to offshore because of the increasing social resistance. This will induce more crossover learning effects and will help some of the problems in the price developments in the offshore wind industry as described in chapter 3.3, such as insufficient capacity at turbine manufactures or skilled labor.

Some regions are concerned with a situation in which they are acting alone in the endeavor to stimulate expensive renewable energy technology to prevent irreversible global environmental change. These concerns are also present with the offshore wind technology in regions such as Western Europe. However there is also a pure market driven perspective to this problem in the sense that once the costs of a certain technology are driven down due to learning-by-doing effects the market will take charge and starts building capacity. In an increasingly global economy the market will buy the technology where its price is lowest, the region where these costs are driven down becomes unimportant. This effect is modeled in TIMER such that regional learning curves are projected globally. In the period 1990-2010 the global specific capital cost of offshore wind decreased from $4411/kW to $2088/kW (in $2005) because Western Europe installed offshore wind capacity. Offshore wind farm developers in South-Korea are already establishing contact with various European offshore wind suppliers to execute the ambitious offshore wind plans (Invest Korea, 2012). Some European and American suppliers have already been acquired by the upcoming South-Korean wind industry.

6 Conclusion and recommendations

Current global energy consumption is expected to continue to grow as the global population is likely to grow towards 9 billion in 2050 while income levels per capita surge with 3-5% per year (IPCC, 2007). Resource depletion, climate change, air pollution and energy security are several reasons to assume that these energy trends are unsustainable. The IMAGE/TIMER model was developed to gain more insight and understanding in the global environmental system. So far, offshore wind power was not taken into account in the projections. This study investigates how offshore wind power can be modelled in the IMAGE/TIMER framework and the impact of this technology on the electricity production in case of different scenarios.

As the offshore wind industry bears great similarity with the onshore wind industry, the technology is modelled such that the specific investment costs are split up into two parts. The first part is similar to the cost of onshore wind as many of its parts such as the turbine, rotor, tower or nacelle can almost be exactly copied from the onshore wind industry. The second part consists of the additional costs to place wind farms offshore such as grid connection, offshore installation costs, higher operation and maintenance (O&M) cost or additional turbine costs. Note that this distinction also has its effects on the technological learning of the offshore wind technology. Furthermore the cost of offshore wind is influenced in three ways. The first is the learning-by-doing effects that indicate cost reductions due to increased cumulative capacity. The second is the depletion effect as additional offshore wind capacity is forced to move to less favourable locations further offshore and to deeper waters as the cumulative capacity builds up. The third way is the additional costs due to its intermittent character such as back-up capacity, extra spinning reserve and curtailment.

Different scenarios and model comparisons were performed to investigate the impact of offshore wind in the modelling projections. The following lessons can be drawn:

1. Modelling results indicate that the offshore wind cost of electricity in 2012 is $10.4ct. Still 43% higher than the cost of onshore wind but steadily moving towards competitive market prices.

2. The inclusion of offshore wind in a baseline scenario resulted in an additional 1445 GW of extra renewable electricity generation capacity compared to a situation without offshore wind. This significant increase of additional renewable generation capacity leads to a 44% increase of the global renewable electricity production share.

3. Regions that account for a significant share in the offshore wind capacity are China, Western Europe, USA, Southeastern Asia and Indonesia. The latter two regions now become interesting players in the renewable electricity industry with the inclusion of offshore wind.

4. The inclusion of offshore wind in a baseline scenario results in a reduction of 84 Megaton annually avoided CO_2 emissions in 2100, a 4% decrease in the total annual CO2 emissions.

5. Modelling results show that offshore specific policy measures had a strong positive effects on the price development in the period 1990 – 2010 but lacks significant

response in later periods. Partly this is because a large part of the offshore costs are determined by the developments in the onshore wind industry and because of rather low offshore progress ratios.

6. In a 2°C climate target scenario with a compatible carbon tax path the inclusion of offshore wind ensures a 44% increase in the share of renewable energy production compared with the same scenario without offshore wind. Offshore wind takes op 35% of the total installed renewable generation capacity. The extra carbon offset due to the inclusion of offshore wind is minimal because much of the internal competition between the different low carbon electricity generation technologies such as onshore wind and nuclear power.

Several model improvements can be made. First, this study shows that inclusion of new technologies can have significant impact on modeling projections and that continued expansion of global environmental change models is important. Second, the off- and onshore wind industry model should include mutual crossover learning effects. Third, recent studies indicate that micro scaling can improve estimations of the global wind potentials significantly. Fourth, the offshore model can be improved by the inclusion of regional economic, political and infrastructure parameters to control for safe investment decisions in capital intensive industries such as offshore wind. Fifth, learning rate estimations can be improved correcting for various depth and distances. And sixth, comparison with other modeling projections is desirable for further improvement.

Overall, it can be concluded that the impact of offshore wind technology on the global electricity system is significant and that it is likely that it may contribute considerably to reverse several of the unsustainable energy trends.

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APPENDIX I – LIST OF WIND FARMS

Wind farm	Country	Year built	Capacity (MW)	Depth (m)	Distance to shore (km)	Investment (€/Kw)
Vindeby	DK	1991	4.95	3.50	1.5	2679
Lely	NL	1994	2	7.50	0.8	2770
Tuno Knøb	DK	1995	5	4.00	3	2485
Bockstigen	S	1998	2.75	6.00	5.8	1635
Utgrunden	S	2000	10	6,0 - 15	7.3	1962
Blyth	UK	2000	4	8.50	1	1570
Middelgrunden	DK	2001	40	6.00	2	1315
Yttre Stengrund	S	2001	10	6,0 - 8	3.7	1462
Horns Rev	DK	2002	160	6,0 - 14,0	18	1821
Samsø	DK	2003	23	10,0 - 13,0	4	1628
Nysted	DK	2003	165.6	6,0 - 9,0	11	1737
North Hoyle	UK	2003	60	12.00	7.5	2055
Scroby Sands	UK	2004	60	8.00	3.5	1901
Kentish Flats	UK	2005	90	3,0 - 5,0	9.8	1762
Barrow	UK	2006	90	12,0 - 16,0	12.8	1630
Egmond aan Zee	NL	2006	108	15,0 - 18	13.7	1885
Lillgrund	S	2007	110	4,0 - 13	9.3	1723
Burbo Bank	UK	2007	90	8.00	8	1706
Q7 (IJmuiden)	NL	2008	120	19,0 - 24	23	3136
Lynn & Inner Dowsing	UK	2008	194	6,0 - 18,0	6.9	2237
Robin Rigg	UK	2009	180	4,0 - 13,0	11.5	2583
Horns Rev II	DK	2009	200	9,0 - 17,0	32	2281
Rhyl Flats	UK	2009	90	6,0 - 12,0	10.2	3023
Gunfleet Sands I	UK	2009	108	2,0 - 15	7.4	2457
Gunfleet Sands II	UK	2009	64.8	2,0 - 15	7.4	2812
Thanet	UK	2009	300	14,0 - 23	17.7	2445
Teesside	UK	2011	90	6,0 - 18	2	2222
London Array	UK	2012	1000	23.00	27.5	2210