Scenarios for offshore wind development in the Netherlands

An agent-based modelling approach

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K. C. A. M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 10 februari 2014 om 15:00 uur

door

Eeke Hendrika Maria Mast

ingenieur in de technische wiskunde
geboren te Hoevelaken, Nederland.

Dit proefschrift is goedgekeurd door de promotoren:
Prof. dr. G. J. W. van Bussel
Prof. dr. R. W. Künneke

Samenstelling promotiecommissie:

Rector Magnificus,	voorzitter
Prof. dr. G. J. W. van Bussel,	Technische Universiteit Delft, promotor
Prof. dr. R. W. Künneke,	Technische Universiteit Delft, promotor
Prof. dr. P. E. Morthorst,	DTU, Denemarken
Prof. dr. G. Brunekreeft,	Jacobs University Bremen, Duitsland
Prof. dr. P. M. Herder,	Technische Universiteit Delft
Prof. dr. G. A. M. van Kuik,	Technische Universiteit Delft
Dr. E. J. van Zuijlen,	FLOW/ TKI Wind op Zee

Keywords: offshore wind, agent-based, social simulation

Printed by: Ipskamp drukkers

Front & Back: C. van Kranenburg, E.H.M. Mast.

ISBN 987-94-6259-055-7

An electronic version of this dissertation is available at
`http://repository.tudelft.nl/`.

Summary

The aim of this study is to develop a method to identify the barriers to and opportunities in the development of large-scale offshore wind energy in the Netherlands, taking into account the uncertainties of the future and consequences of decisions, from technological, economical, social, political and environmental perspectives. The scope is limited towards the target of 6000 MW in 2020. The research question is stated as: can an agent-based model be used to develop realistic implementation paths towards 6000 MW installed offshore wind power in the Dutch EEZ that show the consequences for the stakeholders?

The delineation is described in chapter 4. Topics have been identified that are considered the most important for implementation paths of offshore wind energy in the Netherlands towards 6000 MW. From these topics, the focus topics for the model have been determined: the permit procedures, financial support, layout and timing of an offshore grid, the availability of resources, and innovation, especially of wind turbines.

In chapter 5, four model requirements have been defined to act as guidelines to determine what to include and exclude from the model. The requirements led to the focus on five major parts: the turbines, foundations, electrical system divided in sea-cables and the substation, and the onshore work. The model should include the perspectives of the different involved actors, but the agents as model elements do not represent the actors but their roles. This role-based instead of an actor-based approach for the model development excludes the necessity for a micro-analysis into specific firms. Micro-level assumptions on actor behaviour, to be translated to agent behaviour, are of course still necessary. The actors are considered boundedly rational. This is translated in the model as an incomplete perceived world for the agents over which they have limited information and the possible actions they perceive and are allowed to take are only a subset of all possible actions.

The agents are situated in an environment. Thirteen key environmental

variables have been identified associated with the geographical locations, governmental policy, markets and technological innovation. Four environmental scenarios have been described. The variation in the key variables over these four scenarios indicate that the environmental scenarios span four sufficiently different future images addressing the desired institutional, technological and physical aspects. To simplify the input for the model, several high-low or high-medium-low values have been defined, deduced from interviews and literature.

The results show that the agent-based model can indeed simulate different implementation paths that show the effect of selected input on the desired output parameters. These simulated implementation paths can be used for policy and decision support as a communication tool to show different possible futures and the limiting factors for the implementation in these futures. They can help to identify the relations between decisions and resulting implementation speed, costs for installation and subsidy and the characteristics of the built parks. Different perspectives of different actors can be combined and the modelling of different agents even necessitates taking different points of view on the issue to model each agent. The implementation paths can be (partially) validated using (estimations from) other studies into different future developments. The methodology given in this study provides a step plan to develop such an agent-based model in analysis, design, implementation and validation phases. The agent-based model can certainly be used in an 'insight not numbers' manner, as well as for a relative comparison between scenario runs.

To use agent-based modelling and the presented methodology as a method to find barriers and opportunities, as stated in the aim of this study, some side notes have to be made. The main disadvantages of using agent-based modelling are: the extensive (detailed) data gathering, a long development time dependent on the implementation process and available standards, the required 'mass' and development time before simulations can be made that can be validated, and the limitations in modelling complex actor behaviour. The main advantages of using agent-based modelling are: the model can combine technological and socio-institutional aspects, the model can combine qualitative and quantitative data, the agent-based 'as-is' modelling makes design easier, the model is easily extendable and a computer model is transparent.

Samenvatting

Het doel van deze studie is om een methode te vinden die barrières en kansen kan vinden voor de ontwikkeling van grootschalige offshore wind energie in Nederland. Hierbij moet rekening gehouden worden met de onzekerheden over de toekomst en de verschillende perspectieven op de mogelijke implementatie, vanuit technologische, economische, sociale en milieutechnische hoek. Als uitgangspunt is genomen om te kijken of 6000 MW geinstalleerd vermogen in 2020 behaald kan worden. De onderzoeksvraag is als volgt geformuleerd: kunnen realistische implementatiepaden naar 6000 MW geïnstalleerd offshore wind vermogen ontwikkeld worden aan de hand van een agent-based model, die de gevolgen moet kunnen laten zien voor de belanghebbenden?

De afbakening is gemaakt in hoofdstuk 4. De focus van het onderzoek is bepaald door de onderwerpen die gezien kunnen worden als het meest relevant voor de ontwikkeling van offshore wind in Nederland. Deze meest relevante onderwerpen zijn: de vergunningsprocedures, financiële ondersteuning, de aanleg van een offshore net, de beschikbaarheid van benodigde middelen en de verwachte innovatie, met name van de wind turbines.

In hoofdstuk 5 zijn vier eisen aan het model gepresenteerd die dienen als richtlijnen om te bepalen welke elementen in het model worden meegenomen en hoe. Dit leidde tot een focus op vijf hoofdonderdelen van een park: de turbines, de fundaties, het elektrische systeem bestaande uit een offshore station en de onderwaterkabels, en het werk op land. Alhoewel de verschillende perspectieven van actoren wezenlijk zijn, is het model niet opgebouwd uit representaties van de relevante actoren maar van hun rollen. Hierdoor wordt het model anoniemer en is een microanalyse in de verschillende betrokken actoren niet van belang. Aangezien het model gedrag dient te simuleren, moeten er wel aannames worden gemaakt over actorgedrag. Het uitgangspunt hierbij is dat de actoren begrensd rationeel zijn, zowel in hun perceptie van de wereld als in de acties die zij mogelijk kunnen nemen.

Voor de omgevingsscenario's zijn dertien elementen bepaald, gerelateerd aan de geografie, overheidsbeleid, markten en technologie. De variatie van deze hoofdelementen in de vier gepresenteerde scenarios laat zien dat er vier onderling voldoende verschillende werelden voor de *agents* in het model zijn opgenomen. Binnen elk scenario wordt er een onderling samenhangende keuze gemaakt voor de waarde van de invoerparameters. Met behulp van interviews en literatuurstudie zijn de waarden bepaald, vaak in hoog-laag of hoog-medium-laag waarden.

De resultaten laten zien dat een agent-based model inderdaad implementatiepaden kan genereren. De paden zijn deels gevalideerd aan de hand van (schattingen van) andere studies. De onderzoeksvraag is hiermee positief beantwoord. De gepresenteerde methodologie biedt een stappenplan om een dergelijk model te analyseren, ontwerpen, implementeren en valideren. Vanuit verschillende invoer, gerelateerd aan de omgevings- of gedragsvariabelen van de agents, kunnen zeer verschillende paden gesimuleerd worden. De paden kunnen de relaties laten zien van beslissingen en de gevolgen daarvan op de implementatiesnelheid, kosten voor installatie en subsidie en karakteristieken van de gebouwde parken. Doordat het voor een modelleerder noodzakelijk is om vanuit verschillende oogpunten te kijken om het gedrag van de verschillende betrokken rollen te modelleren , worden de verschillende perspectieven meegenomen in het model. Het model kan gebruikt worden om inzicht te verkrijgen in de implementatie van offshore wind en zijn afhankelijkheden in een 'inzicht maar geen getallen' manier. Tevens kan een comparatieve kostenvergelijking gemaakt worden tussen de verschillende resulterende paden. De paden kunnen gebruikt worden voor zowel beleids- en beslissingsondersteuning als communicatiemiddel om verschillende toekomsten onder verschillende aannames te laten zien.

Een aantal kantlijnen moeten wel geplaatst worden over het simuleren van implementatiepaden door een agent-based model. Om agent-based modellen op een goede manier te gebruiken als methode voor het identificeren van barrières en kansen als limiterende of versnellende effecten tijdens de simulatie , moet men rekening houden met een aantal voor- en nadelen. De nadelen van de aanpak liggen in: het verzamelen van gedetailleerde data; een lange ontwikkelingstijd als er geen gebruik gemaakt wordt of kan worden van standaarden in implementatie en de combinatie van analyse en model- of programmeer experts; de benodigde inhoud van een agent-based model en behorende ontwikkelingstijd voordat de eerste valideerbare simulaties gemaakt kunnen worden, en de grenzen van het kunnen van het model door de keuze van de grenzen van het gemodelleerde systeem en in het bijzonder van actor gedragsmodellering. Hiertegenover staan de voordelen van het kunnen meenemen van technologische en socio-institutionele aspecten ter simulatie van een socio-technisch systeem, de mogelijkheid van zowel kwalitatieve als kwantitatieve invoer, het gemak van het modelleren naar de werkelijkheid, de uitbreidbaarheid van een agent-based model en de transparantie van een computermodel.

Acknowledgements

This work is a contribution to the project PhD@Sea which is substantially funded under the BSIK programme of the Dutch Government and supported by the consortium We@Sea. I am grateful for the financial and organisational support, making this PhD possible.

During my PhD I was supervised by Gijs van Kuik, Gerard van Bussel, Michiel Zaaijer and Rolf Künneke. I would like to thank them for helping me in their own way: Rolf, and the friday presentations at the Economics of Infrastructures section, introduced me to for me unfamiliar topics; discussions with Michiel helped me reflect on my work; and Gijs and Gerard's expertise and vast experience in wind energy are always an inspiration.

I would also like to thank the people who were willing to share information in interviews and the group decision room: wind energy seems to draw very nice people. Thanks to the people at the Wind Energy section and Economics of Infrastructures section, for discussions and also the necessary 'comic relief'.

On a more personal note, I would like to thank my family and friends, especially my Java guru Rutger and photographer Coen. And my deep thanks to Frans, for tiresome proofreading and for the encouragement, he really is the personification of Eek the Cat's statement: 'It never hurts to help!'

Contents

1

Introduction

1.1 A sustainable energy supply

In recent decades, the unsustainability of our energy supply has become an issue of concern. Three basic issues are named as the issues to be addressed for a sustainable[1] energy supply.

First, Europe is dependent on politically restless regions for its energy supply, such as the Middle East and Russia [43] [70]. For electricity generation, most generators in the Netherlands use natural gas. The Dutch natural gas reserve in Groningen gives some independence from foreign countries, and to extend the supply duration the Dutch government has placed caps on production. However, depletion of the Groningen gas reserve is expected by 2030 [255].

Second, all fossil fuels are depletable sources [43] [70]. Estimations when production will peak[2] differ greatly, but all agree that the *cheap* fossil fuel age will end. With the crude oil price per barrel passing over 100 dollar mark in January 2008[3], the importance of finding new resources for energy is stressed again. The rise of new economies such as China and India indicates that a reduction in demand is not to be expected. More fields are coming into production extending the expected reserves, but these fields are generally more expensive to operate and therefore production prices will increase. New extraction methods for shale gas could extend the expected gas reserves for the Netherlands, but shale gas is a controversial topic (e.g. [147]) and has a higher production cost and is therefore only interesting at higher gas prices. A return to low fossil fuel

[1] Here, the term sustainability follows the definition in the Brundtland report, stating: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

[2] The moment of peak oil, where demand starts to rise above the possible production of oil fields, is a major concern for economic growth, as oil prices are then expected to soar.

[3] In February 2013 it is still high, with the European benchmark Brent crude around 114 dollars and WTI at around 93 dollars [49].

prices is therefore not expected.

Third, a sustainable energy supply concerns another important issue: the impact on the environment. In the 1990s smog, acid rain and holes in the ozone layer put environmental issues on the political agenda. The link between emissions from using fossil fuels and global warming renewed the interest. The climate change issue has now been widely accepted as a new challenge for our common future. To tackle this problem, emission reductions are of global concern.

Renewable Energy Sources (RES) are a part of the solution towards a sustainable energy supply. RES refers to non-depletable natural sources that can be used to generate energy at a reduced emission rate, such as solar power, wind power and biomass[4]. Such sources are usually indigenous, as one now uses local energy sources, e.g. the sun, instead of importing fuels. So for a sustainable energy supply, RES are indigenous sources for independence of import and the application of RES reduces emissions and provides independence of depletable energy sources. Therefore targets for application of RES have been set, on a European and national level.

1.2 Wind energy in the Netherlands

1.2.1 Rise of wind energy in the Netherlands

In the application possibilities for RES in the Netherlands, wind energy forms a large contribution. Wind energy in the Netherlands has a long history, as many windmills were installed in previous centuries to drain or grind. There was some small-scale use of wind energy during the second World War as a form of distributed electricity generation and some experimentation with larger machines thereafter, but it was not until the first oil crisis in 1973 that interest in wind energy for electricity generation really began to rise [249].

Because of good wind resources and the Dutch history in wind energy, the Dutch government saw an opportunity for a new industry in which the Netherlands could become a big player [176]. Since the 1990s, siting became difficult for onshore wind projects. The visual impact of onshore locations, such as shadow flicker or simply the presence in the landscape, has caused resistance from local residents. This resistance has significantly slowed down the implementation of wind power in the Netherlands [269].

[4] Although energy generation with the use of biomass emits CO_2, in the whole cycle biomass has a low CO_2 emission rate because the plants forming the biomass use CO_2 during their lifetime.

1.2.2 Moving offshore

Attention has been increasingly focussed on offshore wind, even though this has certain disadvantages compared to onshore wind. The offshore location itself makes offshore wind more expensive compared to onshore wind. The foundation is more expensive offshore, as the structure has to withstand wave loading. The installation at sea and the necessary offshore grid connection add to the costs. Harsh North Sea conditions (e.g. waves and salty air) decrease the weather window for installation and maintenance activities. This lower accessibility of an offshore site can decrease the availability of a park. Since there is little long term experience with offshore wind parks, the environmental impact of a wind park at sea is uncertain, especially the cumulative effects that several parks together might have.

These disadvantages are weighed however against the advantages. Wind speeds are higher, resulting in more produced energy[5] and less turbulent winds offshore give a more constant wind load on the structures. Therefore offshore sites offer a good wind resource for wind power generation units, while at the same time visual impact and noise hindrance for local residents is avoided or reduced. Because of the heavy weight given to these advantages over the disadvantages in some countries (including the Netherlands) the focus is placed on offshore wind.

1.3 Implementation of offshore wind in the Netherlands

1.3.1 Targets for wind energy

The transition to a sustainable energy household is receiving much attention in the Netherlands and offshore wind is considered to play an important part in this transition. Several targets have been set for emission reduction and the application of Renewables. The Kyoto protocol was the first global agreement to reduce emissions rates [189]. In the Kyoto protocol, the Netherlands committed themselves to a reduction of CO_2 emission of 6 % in the period 2008-2012 compared to the CO_2 level in 1990. In December 2008, EU member States stated their target for 2020. The emissions should be reduced by at least 20 % below the 1990 levels and RES should have a 20% share in the energy use [71]. The Netherlands has stated a target of 20% by 2020 [126].

Wind energy has an important role, being a renewable energy source available in abundance in the Netherlands. A large part of the Dutch wind energy is planned to be placed offshore, in the Dutch Exclusive Economical Zone (EEZ) of the North Sea. In the 2002 governmental Energy Report [178] the potential target of 6000 MW offshore wind energy by 2020 is stated as a ‘necessary step

[5]The power production is proportional to the *cube* of the wind velocity

in the transition to a sustainable energy household' in the Netherlands. A cost-benefit analysis performed in assignment of the Government stated that offshore wind energy would become economically viable in the Netherlands around 2025 [251]. The Energy Report of 2008 restates the 6000 MW target by 2020 and sets a short term target of 450 MW by 2011 [181] [149]. In a 2010 study [126], it was stated that the 2020 target could not be achieved without wind power offshore, and alternatives are still in a stadium or research and development.

1.3.2 Issues hindering the achievement of targets

In the beginning of the eighties, the first governmental target for the implementation of wind energy in the Netherlands was set but this proved too optimistic. When the actually realised cumulative capacity showed to be lower than first imagined, later governmental targets were tempered to lower levels and these eventually proved closer to (and even lower than) realised capacity. Implementation has lagged behind countries as Denmark and Germany, however. This had its effect for the industry. Partly due the strong home market, Danish and German wind turbine manufacturers have thrived, while Dutch turbine manufacturers have gone out of business (see for instance [249], [250], [243]). In [259] this is explained as[6] 'when the government support for wind energy stopped in the beginning of the nineties, while the rest of Europe was encouraging wind energy, the wind industry left the Netherlands'.

The target of 6000 MW offshore wind power in the Netherlands by 2020 could help achieve the emission reduction targets and support the Dutch industry in a home market. The installed power of 220 MW in 2010 is however still a long way from this target and as history tells us, optimistic targets are not enough to achieve the implementation. While new opportunities might be found, there are barriers that need to be removed. These barriers and opportunities first have to be identified. The following examples will illustrate some of such barriers and opportunities.

Example 1: Conflicts of interests with other users

Looking at the sea from the shore, the North Sea might appear empty. However, there are many activities taking place, and certain areas of the North Sea have been assigned to some of these activities. There are e.g. military areas, shipping lanes and dredging zones. Siting of wind parks will have to take into account other fixed structures such as oil platforms and pipelines as well as mobile structures such as ships. Offshore wind energy is the 'new kid on the block', and other users will have to 'make room' for this new application in the North Sea. The National Spatial Strategy 2004 document [142] states the necessity and use of offshore wind energy as considered proven. Therefore an individual permit request for a park does not have to provide proof of the use and necessity, but

[6] Translated from Dutch.

it will have to show that the park does not diminish safety for the other users.

One group of other users has shown itself especially concerned about the new kid. Several nautical groups have expressed their concern for shipping safety (e.g. [256], [153], and it is unclear what distance should be maintained between shipping lanes and offshore parks. UNCLOS[7] states that a safe distance of 500 m should be maintained by ships to fixed structures. However, a park consists of several fixed structures and might require a larger distance, since there are less deflection possibilities.

The other users of the North Sea also include the local natural life. The environmental impact of offshore wind parks is still unclear. The extensive monitoring programmes of the parks Horns Rev, Nysted and OWEZ[8] have shown primarily positive results but still leave some questions unanswered. One of the difficulties is that it is hard to distinguish a natural temporary habitat loss caused by a natural movement of the population from location to location from a habitat loss caused by the presence of an offshore wind farm [130]. Now some experience has been gained by parks, but the cumulative effects of several parks require special attention.

Example 2: Other markets affecting turbine price

Learning curve theory tells us that the price of offshore wind turbines could decrease as experience is gained. However, material prices also have an effect. Rising industrialism, especially the rise of China and India, had caused the steel price to climb and since the current turbines have steel as their main material, turbine price had risen accordingly, despite learning effects. The soar in new onshore wind energy markets, e.g. in India, China and the US [30], has caused some wind turbine manufacturers to focus on this lower-risk market. Project developers that are planning offshore wind parks are thus faced with a sellers' market for offshore turbines in which the desired profit margin for turbine manufacturers increases. These examples of parameters influencing the costs of an offshore wind turbine show that these costs are hard to estimate due to the uncertainty of the future dependencies.

Example 3: Availability of resources and timing

For the implementation, many resources are required; 'hardware' such as vessels and factories, and of course money and personnel. To not form a barrier for the implementation, enough hardware needs to be available and investments are required for this. If the implementation is delayed, the years directly prior to 2020 will have to have a high implementation speed to still achieve the 6000 MW target by 2020. But if no investments are made to create more installation vessels (as possible due to a lack of market confidence because of the delay),

[7]The United Nations Convention on the Law of the Sea.

[8]Offshore Windpark Egmond aan Zee

there may not be enough installation vessels available.

Supply chain issues have already been identified as an issue in the implementation of offshore wind, as long lead times are found for for instance turbines and transformers ([78], [89]). For an optimal use of one's investments in hardware, a smooth implementation is required so the hardware is used at maximum capacity. However, if one wants to take advantage of (international) learning curves, a late national implementation could save money. This could lead to an under-investment in the 'hardware' and an increased implementation speed near 2020 might not be possible because of the lack of available vessels, turbines etc. Timing is therefore an important issue in the implementation, and it ties to the issue of the availability of necessary resources.

Example 4: Governmental policy and support

The development of offshore wind energy provides new opportunities for the offshore industry, a sector in which the Netherlands is strong. Developers have shown interest in implementing the political ambition of large-scale offshore wind power installed in the Dutch part of the North Sea, based on the number of initiatives and permit requests. However, for an offshore wind sector to flourish, institutional support is required to streamline the development. This includes a dependable financial support scheme from the government combined with a long term, stable governmental policy for permitting. This combination can boost implementation and reduce investment risk. Once offshore wind is economically viable, the subsidies will no longer be necessary. For deciding such financial support, the competition level with other types of generating units needs to be taken into account, in for instance hidden subsidies and grid connection issues.

However, regulatory uncertainty has diminished the developers' enthusiasm. Permit procedures and subsidies have been frozen and adapted several times. In the Netherlands, the moratorium for offshore sites was lifted at the end of 2004 and project developers could make a start for projects in January 2005. By the end of 2005, over 70 initiatives were placed for about 30 different sites. The Ministry of Economic Affairs, who handled the production subsidies, feared offshore wind would spend to much of the national budget as there was no financial control incorporated in this open-ended subsidy scheme [57] and the subsidy scheme was abolished in August 2006.

Not until November 2009 has the new support scheme been presented, bringing a new system of tendering for production-base subsidies. Receiving a permit does not secure a subsidy anymore, while costs do have to be made to attain the permit. This subsidy scheme, the SDE (Subsidieregeling Duurzame Energie) [145], followed the announcements in the government programme 'Clean and efficient' [149]. In this programme, it was stated that after 2011 problems around finding locations should be solved and 500 MW per year should be implemented. It also states that cost reductions by innovation are required. But the following support system, the SDE+, for 2011-2014, only states subsidy for offshore wind parks is available in a 'free category', because of the expectation that most parks will cost more than the upper limit of 15 €cents/kWh [146].

1.4 Future views on offshore wind implementation

1.4.1 A complex socio-technical system

An energy transition is necessary towards a sustainable energy supply and offshore wind power can have an important contribution. The examples in the previous section show that achieving the implementation of 6000 MW of offshore wind energy is not just a technical puzzle or a cost-minimisation problem. When regarding the possible implementation of offshore wind energy in the Netherlands, one is regarding a *socio-technical system*, where political, social, economical, environmental and technological issues are combined. Socio-technical systems can be understood as: 'systems at the sectoral level ..., made up by a cluster of elements, involving technology, science, regulation, user practices, markets, cultural meaning, infrastructure, production and supply networks' [87]. A socio-technical system combines technology, actors and their institutional setting with an existing infrastructure in a geographical setting.

Here, the socio-technical system under investigation are 'the cluster of elements' involved in the implementation of offshore wind power in the Netherlands. These elements are technical elements such as turbines, the national grid and vessels; and social elements such as legislation and actors. Innovation changes the characteristics of the technical elements. The actors form a diverse group: e.g. nautical groups, wind turbine manufacturers, offshore installation companies and governmental agencies. These actors influence and are influenced by the implementation and their own interest in the implementation. The actors have strategies to look after their interests and adapt to changes in their environment. The many interacting and adaptive actors, combined with the social and technical artifacts, indicate the complexity of the system.

The implementation of offshore wind into the Dutch electricity system is part of a complex socio-technical system. In regarding a socio-technical system, the complexity hinders a complete overview. Potential barriers impeding the implementation or catalysts speeding it up are not self-evident because of this complexity and because of the uncertainty of events in the future. Many uncertainties have to be taken into account, as one cannot predict the future: the analysis of a future state is not a simple trend analysis.

1.4.2 Finding barriers and opportunities: an integrated approach

To help decision makers, one would like to know the possible barriers or catalysts of the future in advance, to be able to prepare for them. As it is not possible to predict the exact development of a socio-technical system, because of the uncertainty and complexity, the question remains: how can possible bottlenecks, slowing the implementation down, and possible catalysts, increasing the implementation, be found?

Several topic studies have been made in the multi-disciplinary field of offshore wind energy related to its future development in the Netherlands, from cost estimations to grid studies[9]. General studies have focussed on the identification of the issues which could become of importance for offshore wind in the Netherlands, as a barrier or a catalyst. Often such studies project current data forwards (trend analysis), making estimations based on available data (e.g. [73]) to see whether and when these issues will start to play role. Uncertainty over the future is sometimes taken along by presenting several paths. Such studies usually consider the development of offshore wind energy in a country from a macro level view and focus on certain technical or economical issues instead of taking an integrated approach.

Insight is required in the possible and realistic development of offshore wind energy in the Netherlands towards 6000 MW by 2020. A method is required to be able to give insight in possible barriers or catalysts to this development, taking into account the uncertainty over the future and taking an integrated approach to examine the (possible) issues for the decision makers. This should be done in a manner that can address political, social, economical, environmental and technological issues in this complex socio-technical system. This requires an integrated approach that combines information from different topics.

Different actor perspectives

The field of offshore wind includes many actors influencing or being influenced by offshore wind. These actors have different perspectives on what possible barriers and opportunities can arise and what solutions can be given. Even a shared objective of ‘realising 6000 MW of offshore wind energy’ will not result in all actors following a shared strategy towards this objective.

This is because the actors have different interests in the field. A project developer will have more concern for the economic viability of a project while an environmental group will focus on the environmental impact. In locating wind parks both the interests of developers and other users of the North Sea (human and other animals) should be taken into account. Another example

[9] Such studies are for instance the grid studies [180] [182], the studies in the DOWEC project [195], or the cost-benefit analysis [251] of the CPB

of interacting actors and differing interests is the possibility of an offshore grid connection point ('socket at sea'). This can cut overall connection costs if there is no under-utilisation of the 'socket' [180]: regulation or cooperation between government, grid operators and developers can avoid under-utilisation of the cable. Conflicts of interests can lead to compromises, or barriers.

The differing strategies of actors will influence the timing, and since the target of 6000 MW is set at a time horizon at 2020, this timing is of importance. The implementation speed depends on the availability of resources and the amount and characteristics of the available resources. For instance, the number of parks that can be built in a year is dependent on the number of available installation vessels and the capacity of the wind turbine manufacturing. Such resources are ruled by actors, by investment in innovation or in new resources. For example, a harbour manager deciding to expand suitable harbour area for offshore wind, a wind turbine manufacturer expanding (or decreasing) its capacity for offshore wind turbines. Actor behaviour therefore also influences the implementation speed in a very direct, physical manner.

1.4.3 This study

Insight in the possible developments would help the involved actors prepare for the future. Certain questions remain unanswered by current methodologies and studies: can information and results from other studies be combined in paths that show possible routes the implementation might follow, taking into account the different perspectives of the involved actors without assuming complete co-operation and perfect timing? The different actors have different views on what the desired implementation would be, as they have different perspectives and therefore set different conditions on the implementation; conflicts of interests could arise.

For possible developments of the implementation of offshore wind in the Netherlands, the different perspectives of the actors have to be taken into consideration. A method should be found that can find barriers and opportunities by examining actor strategies, the availability of resources and the time dependence of change. This method should have an integrated approach, combining technological, economical, political and environmental aspects, as required by the change to the socio-technical system that is reviewed when looking at the implementation of offshore wind energy. In this thesis, this will be addressed by creating several possible paths for the implementation based on the actions of actors, by simulating a society of actors. This is explained below.

Implementation paths

To find possible barriers, one could look at different ways this implementation could come about, to show what the necessary steps are at crucial points in time. Here the different possible routes of implementation are named *implementation* *paths*. An implementation path offers a possible view on the development of the implementation or application of a technology in a certain area. An implementation path can be seen as a time path for the implementation of offshore wind in the Netherlands. In an implementation path, the issues that inhibit a faster or higher implementation, the critical issues, can be identified and their effects can be shown.

Micro-founded by actions of actors

To aid the involved stakeholders, the implementation paths should give insight into the future to which actions of actors could be taken at which times and their consequences on the implementation of offshore wind energy. The stakeholders involved are the actors that can influence or can be influenced by the implementation and that therefore have an interest in the future for offshore wind power. In different implementation paths different strategies could be examined in different situations to see how they influence the achievement of 6000 MW. The development is seen as built up from the bottom-up by the actions of these actors: the development is seen as *micro-founded* by the actions of actors [46]. The socio-technical system is regarded from a micro-level, instead of from a macro viewpoint, to include the actors' strategies.

Simulating a society of actors

To create implementation paths, a computer model will be developed. In a computer model, the dynamics and parts of this system are formalised to deal with the complexity and to ensure consistency and transparency. By explicating the variables and their interrelations, transparency is realised towards the decision makers as to what exactly has been taken into account and what the underlying assumptions are. Consistency is achieved by identifying the relations between variables. The model will have to deal with qualitative data as external input data and quantitative data.

The simulation model is to represent the changing complex socio-technical system, with its many different actors and perspectives, as well as the different issues or factors that could influence the implementation. To be able to include the different perspectives of the involved actors, the computer model would be a simulation model that reflects the (types of) interacting actors. In a simulation, one can investigate how macro-level changes can arise from micro-level changes or, in other words, how system changes can be micro-founded by actions of individuals or groups of individuals.

Simulating a system from a micro level has already been done in *Micro-Simulation*, where macro-level changes are examined by micro-level modelling [37]. In Micro-Simulation the system is cut up in subsystems with their separate behaviour and changes. There is however no interaction between the different parts. In the newer *Agent-Based Modelling* (ABM), the micro-level modelling grew as a simulation paradigm where the focus lies on interacting agents that represent the interacting actors. An agent can be described as a computer program or module that models a self-directed entity: it takes action towards its own objectives, for instance a human looking for food or a company wanting to make a profit. An *Agent Based Model* is a model consisting of several interacting agents, as a computer representation of a complex system comprised of multiple, interacting actors (i.e. agents) [116].

1.5 Research objectives

1.5.1 Aim

This research aims to examine if a computer simulation model can provide insight in the possible and realistic development of the large-scale implementation of offshore wind power in the Netherlands. As stated, the implementation of offshore wind energy requires changes to a socio-technical system, as realising 6000 MW installed offshore wind power in the North Sea is not just a cost minimisation problem or technical puzzle, combining economical, technical, social, political and environmental aspects. A model is to be developed to identify the critical issues: what could hinder or expedite the implementation.

The aim of this PhD research is therefore defined as:

> Examine if a model can be used to identify the barriers and opportunities to the implementation of large-scale offshore wind energy in the Netherlands, taking into account the uncertainties of the future and consequences of decisions, from technological, economical, social, political and environmental perspectives, towards the 6000 MW target.

1.5.2 Research question

In this study, the perspectives of different actors on the implementation and how their actions could influence this implementation are considered key and the dynamics of change of the system are therefore considered micro-founded by the actions of actors. These actions include managing resources, and the availability of resources should be included to account for time to change and the timing of realising 6000 MW by 2020. The developed model has to represent the different objectives and interests of the involved actors, the availability of resources and constraints on resources and agents in physical, regulative and cognitive aspect.

In this research it will be examined if implementation paths can be developed in a meaningful way using an agent-based simulation model. It will be examined if agents can be modelled to represent actors and their perspectives, resources, constraints, objectives and interests in a realistic manner, and if one can use the model to create implementation paths that can identify critical issues, and assess the impact of a possible implementation path on the actors. The possibilities and ease of including qualitative and quantitative data are examined. The manner in which different future surroundings can be taken along are examined.

The research question is therefore defined as:

> Can an agent-based model be used to develop realistic implementation paths towards 6000 MW installed offshore wind power in the Dutch EEZ that show the consequences these paths entail for the stakeholders?

The following sub-questions have been formulated to help answer the main research question:

- Which steps can be identified for the development of an agent based model of the implementation of offshore wind in the Netherlands?
- Which issues can be identified that influence the implementation, considering the history, current status and future outlook of offshore wind energy? Which are considered the most important?
- Who are the actors involved in the development of offshore wind in the Netherlands and what are their interests, strategies, resources and operational procedures?
- How can actors be presented as agents in an agent-based models? How can the behaviour and capabilities of the actors be described and represented as behaviour of agents?
- What are relevant and consistent environmental scenarios to determine the environment of the agents in the agent-based model?
- What can be deduced from the created implementation paths as challenges and opportunities for offshore wind in the Netherlands towards 6000 MW in 2020? What can not be deduced?

1.5.3 Scope

The implementation paths show only the possible implementation of offshore wind in the Netherlands, in the Dutch part of the North Sea. The selected target is 6000 MW of offshore wind, following the governmental target of desired installed power by 2020. Even though only installed offshore wind parks in the Netherlands are of interest, the technology development of offshore wind energy is considered to be determined on an international level.

Specific firms are not analysed. The different interests of actors involved and the different perspectives they have on the implementation are of importance.

The agents in the model will therefore represent the different actors involved (with their interests and attributes), but an agent will not represent a specific organisation or individual.

To address the research question, a delineation has to be made to what elements of the socio-technical system will be included. A choice will be made to select the most important factors after an assessment of the current status and possible future developments. A *factor* refers to an issue that can influence or be influenced by the implementation of offshore wind energy, e.g. the price of steel and the regulatory uncertainty. The focus of this research will be further delineated after an analysis of the most important factors.

1.5.4 Approach

To assess if an agent-based model can be used to create implementation paths towards 6000 MW installed offshore wind capacity, such a model will be developed. This means that the socio-technical system has to be demarcated to determine which agents and other aspects should be included. In this agent-based model, the involved actors should be represented by the agents, reacting pro-actively and reactively to each other and their environment. The agents actions should be constrained, by both physical and institutional constraints. In the model time steps, the agents should manage their resources and make their decisions, to include the timing and (strategic) availability of resources. The agents should be placed in a range of different futures, to span the uncertainty of the future. To create such different futures, scenario planning is used.

The sequence of the sub-questions shows the step-by-step approach: first the steps in the development of the model will be addressed, in other words the methodology for the model development will be formed. After subsequently identifying the issues, the involved actors, their behaviour and the environment, the model can be implemented and it can be assessed what can and cannot be deduced from the model.

To assess if the research question can then be answered positively, several conclusions will be drawn: on how well the model can be used give insight in barriers and opportunities within different futures; on how it can show the impact on individual stakeholders; on how well it captures reality up to a level; on whether an integrated approach is possible, including political, social, technological, environmental and economical issues developing together within a simulation; and on how well certain general model requirements can be met, e.g. transparency, consistency.

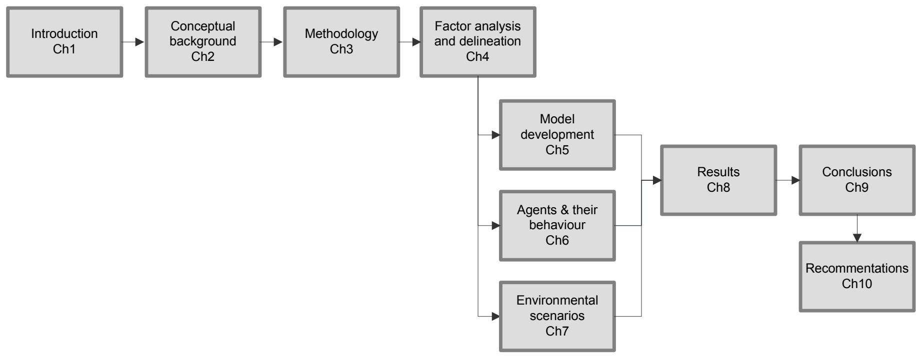


Figure 1.1: Outline of thesis

1.6 Outline and guide

1.6.1 Outline of thesis

The outline is graphically depicted in figure 1.1. In chapter 2 the conceptual framework of the thesis is discussed. This chapter will explain the theoretical view on the reality that should be captured by the model.

In chapter 3, the methodology is explained, starting with an introduction into agent-based modelling and scenario planning. It is described how these are combined in the methodology for this thesis as the step plan to create implementation paths using an agent-based model, consisting of agents, their behaviour and their environment. In chapter 4 the delineation of the study is made by gathering information from literature, interviews and a brainstorming session with several involved actors.

In the next chapters, chapters 5-7, the model development is explained. In chapter 5 the relevant background is given on how the real world is regarded and modelled, followed by an identification of the elements of the model. The elements of the model are the agents and their environment. Chapter 6 describes the agents and their behaviour, while chapter 7 describes the choices and assumptions leading to the development of the environmental scenarios. These environmental scenarios give a range of future environments for the agents.

In chapter 8, the results are given of several development paths describing different implementation paths to 6000 MW. These paths are evaluated and barriers are examined. The conclusions are given in chapter 9. These conclusions address the research question to conclude on the suitability of the approach.

1.6.2 Reader's guide

The approach in this thesis from a more theoretical background is explained in chapters 2 and 5 (especially section 5.1). Chapters 8 and 9 present the model results and the answer to the research question posed in this chapter.

The modelling approach and methodology of this thesis are presented in chapters 3 and 5. These chapters give an introduction in agent-based modelling and explain how the agent-based model is created. In chapters 8 and 9 the results and views on the modelling technique and methodology are discussed. For information on the results, especially sections 8.3, 9.2 and 9.1 will be of interest.

The content of the model is presented in chapters 5, 6 and 7. These three chapters describe the model from the model requirements to the chosen input parameters.

For those interested in the field of offshore wind energy, chapter 4 will be of interest. This chapter describes an investigation in the current status and the choice of the most important topics for the achievement of 6000 MW by 2020.

2

Conceptual framework

Introduction

In this chapter the theoretical background for this study is presented. First the main concepts are explained: socio-technical systems, the co-evolution of institutions and technology and multi-actor perspectives. Second, the concept of an implementation path is explained as a socio-technological trajectory. Third, the framework used for this study is presented and the impact on the (development of the) model is explained.

2.1 Change of socio-technical systems

2.1.1 Socio-technical systems

In this study, the implementation of offshore wind energy in the Netherlands is considered, to explore the normative target of 6000 MW by 2020. This implementation is not only dependent on the development of offshore wind technology. For example, the inclusion of 6000 MW offshore wind energy in the Dutch electricity system will impact the Dutch electricity system, and vice versa the structure of the electricity system will influence the implementation of offshore wind. One cannot only regard the technology itself: the technology under consideration is considered a part of a larger *socio-technical system*. A socio-technical system is a system consisting of both social and technical elements, where the 'technological components and social arrangements are so intertwined that the successful design of such systems require the joint optimisation of technological and social variables' [21].

Socio-technical systems include technical artefacts: methods, knowledge, physical artefacts as natural resources, factories and infrastructures, as well as social artefacts: actors (individuals or organisations) from supply and demand side (in short, both 'the engineers and the users') and the institutional environment governing their actions. A socio-technical system is therefore 'made up by a cluster of elements, involving technology, science, regulation, user practices, markets, cultural meaning, infrastructure, production and supply networks' [87]. In this chapter first the mutual development of the social and technological aspects are discussed, then attention turns to the multi-actor aspect of socio-technical systems.

2.2 The co-evolution of institutions and technology

2.2.1 Socio-technical system change

A socio-technical system is not static, and in this study it is the change of a socio-technical system that will be examined, specifically: the implementation of large-scale offshore wind in the current electricity system. Change to the socio-technical system therefore involves both technological change and institutional change. In the next paragraphs, technology and institutions will be defined and technological and institutional change will be discussed.

2.2.2 Technological change

Technology is a combination of knowledge, tools, devices, equipment, and methods [88]. Physical artefacts form the material or 'hardware' side, and include physical structures such as equipment and devices pertaining to the technology itself as well as relevant technologies from the sectors it is in contact with.

The physical artefacts have an influence on possible technological developments. This hardware can represent large investments and change can mean complete replacement is required. For instance, infrastructures generally have a large inertia due to the large sunk costs in investments in physical artefacts. Changes to the physical artefacts can therefore require a long runtime and this affects the implementation speed. Physical elements are also dependent on the geographical location. The geographical situation of an area can exclude certain technical possibilities, for instance the mountainous Switzerland is geographically better suited for hydropower than the Netherlands. For the implementation of offshore wind in the Netherlands, the geographical aspect concerns the wind resource and other local characteristics of the North Sea. Several studies show that the Netherlands has a good potential for offshore wind due to the strong wind resources and shallow sea water of the North Sea (e.g. [139], [73]).

Technological development has been described to follow a certain path, the *development path*, as an s-shaped life cycle model or growth curve which can be divided into different phases: the introduction phase, the expansion phase, the saturation or maturity phase and finally stagnation and/or deterioration phase. In the introduction phase, an invention is commercially introduced and (only then) becomes an 'economic fact' [194], following Schumpeter's distinction of the invention, the innovation and diffusion. An innovation can still have only limited impact, but this increases as the innovation is widely diffused (the expansion phase) and mass adoption of an innovation is realised.

The progress along this development path of the technology is not a random process. In the theories of technology-push and demand-pull for technical change, demand-pull describes technological change as instigated by changes in demand, whereas technology-push describes change arising from innovation which then changes market demand. Dosi [58] states these views do not do justice to technological change. He states technological change is limited by the set of readily available technological possibilities, and the manner in which economic factors shape the direction of technical change. Dosi [58] calls the path of technological change a *technical trajectory*. He states that this trajectory is not a path to the optimal solution, but is influenced by the methods available to the engineers and their way of thinking towards solutions, as the engineers work within a certain *technological paradigm*, defined by Dosi as:

> "An 'outlook', a set of procedures, a definition of the 'relevant problems' and of the specific knowledge related to their solution."

The technological paradigm can be understood as a certain way of thinking towards how progress can be achieved. Engineers work in a certain paradigm of thinking towards a solution. It determines not only which solutions are available to the engineers, but it also determines which problems are identified by the engineers. As the engineers work in the direction of the prevailing paradigm, innovation follows technical trajectories and not a random process or a process purely guided by demand.

Change along a technical trajectory tends to be incremental change. Incremental innovation is technological change in small steps such as improvement of existing products and processes [194]. In [194], Perez states there is a recognisable logic in the main trends as incremental technological change, making certain forecasting possible for technology development. The Abernathy-Utterback model (described by Clark in [36]) describes a more transitional change in technological development: its development starts in a 'fluid' stage where innovation is rapid and fundamental to a highly specific and rigid state characterised by standardisation and dominant design approaches. Such rapid and fundamental innovation is called radical innovation. Radical innovation does not follow patterns as described above. A radical innovation or change can cause a paradigm shift and the creation of a new trajectory as a 'new technology' can arise. Take for instance the impact of the microchip. The super-large transistor tubes in computers could be replaced by cheaper, smaller components, making personal computers possible and available in the workplace, causing changes in the selection of solution methods as for instance cheap numerical approximation became possible. Such a new trajectory (or new trajectories) can run along the continuation of the old trajectory, until it may replace the old trajectory entirely[1].

2.2.3 Institutional change

Before continuing with paths and trajectories, institutions and institutional change is touched upon. Institutions are considered the 'rules of the game' where 'the game' refers to economic interchange or behaviour[2], following North's definition, as he states [170]:

> ['Institutions are] humanly devised constraints that shape human interaction.'

Institutions guide the behaviour of actors and influence what actions they can take [6]. A division can be made into formal and informal institutions [171]. Informal institutions are the unwritten rules of society: the customs, traditions and norms. Formal institutions are the written rules of a society. They are written down in legislative and regulatory rules: e.g. constitutions, laws and property rights. The formal institutions can be seen as manifestations of the underlying norms and values (the informal institutions) [99]. Together the informal and formal institutions form the institutional environment of actors as 'the rules of the game' [172]; political, social and legal rules that define and support the transactional activities of the actors.

An example of an informal institution impacting the implementation of offshore wind is the cultural valuation of the open view to sea: inhabitants of coastal regions and tourists have opposed to parks near to the coast because of their valuation of the visual impact. Examples of formal institutions applying here are the Water Act under which project developers have to file their request for an offshore permit for an offshore wind park.

The manner in which the 'rules' are applied can vary, e.g. in the methods of the organisation of transactions in institutional arrangements such as contracts and company policies; and in the institutional structure of production [38], by organisational structures such as private or public firms and vertical integration. So seeing the formal and informal institutions as the formal and informal rules humans follow in their economic behaviour [171], the institutional arrangements are the actors' methods and processes for using these rules [38]. In a framework including these different types of institutions (formal and informal institutions, institutional arrangements), Williamson recognised four levels of social analysis, depicted in table 2.1 ([265], [266]). Each layer has its own general frequency

[1] As an example in energy supply: turf has been entirely replaced by coal for generating energy for e.g. heat, while several trajectories can be seen now as coal is used in combination with e.g. oil, natural gas, and renewable energy sources for heat and electricity.

[2] The term institution is defined in several ways, leading to institutions as the 'rules of the game', the 'players of the game' (organisations) or the outcome (equilibrium) of the game [6].

and purpose of change [100].

Table 2.1: Williamson's framework for levels of social analysis. The frequency is in years.

	Level	Frequency	Purpose
• L1	**Embeddedness** (Informal institutions)	$10^2 - 10^3$	Often non-calculative, spontaneous.
• L2	**Institutional environment** (Formal rules of the game, esp. property)	$10^1 - 10^2$	Get the institutional environment right, first order economising
• L3	**Governance** (Play of the game, esp. contract)	$1 - 10^2$	Get the governance structure right, second order economising
• L4	**Resource allocation and employment**	Continuous	Get the marginal conditions right, third order economising

The first level is the level of informal institutions: the unwritten rules or 'culture' of society [265]. These are slow to change as they are deeply embedded in a society: the change frequency is described by Williamson as varying between the order of a century to even a millennium. Level 2 consists of the formal institutions, where change is in the order of a decade to a century. In the exceptional cases of highly disruptive events the first and second level can have faster change, e.g. wars or financial crises. The third level consists of the institutions of governance. Governance structure decisions can for instance be a decision to obtain a product from the market or produce this within the firm. Not just production costs are taken into account, but also the transaction costs, as for instance contracts have to be drawn up as safeguards against opportunism and such contracts (may) need to be enforced (in court). Governance structure changes typically occur between 1 and 10 years. The fourth level is the allocation of resources and the employment of firms in order to maximise their profit. This is the focus of neoclassical economics and its focus on price, output and marginal price setting; and of agency theory, where risk aversions of actors are differentiated. Changes in this last layer can occur on a daily basis.

2.2.4 Interaction institutional and technical change

The change in a socio-technical system consists of the change of both its technical and social elements. For offshore wind energy, examples of relevant technological change refer to (both incremental and rapid) innovations such as larger, more reliable turbines or stronger interconnections between national grids. Examples of institutional change relevant to offshore wind energy implementation are changes to institutions such as regulation and the financial support arrangements, the willingness of companies to invest and the measure of environmental concern leading to social support from society.

But the above descriptions of technological and institutional change have left out an important aspect: technologies affect institutions and vice versa. Institutions have an effect on the development of a technology and technological change as they set the conditions on the implementation as to what is desirable, acceptable and possible. In this respect, it is said that institutions form the selection environment for innovation and technology choices, and institutions therefore shape and mold innovation processes [160].

In return, technology influences institutional change. For instance, key public policy issues affecting technology deployment are not seen as static but as changing in time [159], and these changes are dependent on the industrial structure and the technologies being employed. Perez [194] states that the diffusion of new technologies guides socio-institutional change, although there is a delay due to the inertia of past successes and vested interests. Perez therefore states that institutional development usually lags behind technological development (Perez as cited in [212])[3]. Saviotti [212] states that if one combines this with the assumption that institutions are required for the complete development of a technology or a set of technologies, then the technology life cycle duration depends on the duration of institutional change.

So institutions influence technology, and technology influences institutions. The development and functioning of a system can only be explained by understanding their socio-technical nature [254]: one has to take into account that the system is built up out of interacting social and technical elements. Nelson and Winter captured this mutual influence of technology and institutions in the development of a technology by stating that technology does not follow a technical trajectory, but a *socio-technical* trajectory [160][4]. Technology does not change completely according to the choices and practices of the engineers: other actors influence the technology development path as well. For instance users have an influence: a certain technology development might be in high demand (similar to *demand-pull*). Institutional change can enforce technological change, as for instance certain unwanted effects arise after the application of a technology and regulation is set in place to deal with these unwanted effects. Institutional change can follow technological change [194], as technological progress influences people's needs and expectations (similar to *technology-push*).

Previous institutional and technological choices influence the development

[3] As an example, one of the reasons the second Dutch offshore wind park has smaller turbines than the first, is because their permit was given first and for a certain type of turbine. By the time the park was actually going to be built, a larger turbine was available but then a new permit would have been required.

[4] Note that this is not the same as their 'natural trajectory', which represents the path a technology follows after the problem solving activities have been chosen and established [160]

of a technology in its socio-technical trajectory: the technology development is *path-dependent*. In path dependency, a certain chosen route is reinforced after its initial selection in positive feedback mechanisms - in other words past choices can reinforce themselves in future choices. Such positive feedback could arise for a certain technical choice as it becomes part of the everyday tools and way of thinking for engineers, or surrounding actors such as users create economies of scale for a certain development. The 'QWERTY' keyboard is a famous example of path dependency, as the QWERTY configuration was designed so the arms of an old typewriter would not hit each other for the most frequently used letter combinations. The modern day keyboard still uses the same configuration, because people are used to this configuration. For the energy sector, the choice of 230 Volt for households is an example of path dependency. The voltage for electrical appliances is set according to this standard. A unilateral change of delivered voltage by the national grid operator would impact all electrical appliances already present in the house: the consumer will most likely not be happy with having to buy voltage adapters for all his electrical appliances.

2.2.5 Co-evolution

Summarising, institutional change is dependent on the type of institution and it is influenced by technology, whereas the development of a technology depends not just on its most visible elements [109], but on the current methods, practices, technologies, and its institutional setting. The mutual influence of technologies and institutions explains that their change over time is not independent of each other: they influence each others development or 'evolution' along the socio-technical trajectory and this trajectory is path-dependent. This influence is expressed by the term *co-evolution*[5] of institutions and technology, stating that institutions and technology develop together, the one influencing and being influenced by the other [161].

2.2.6 An illustration of historical co-evolution of technology and institutions in wind energy

As a short illustration of co-evolution of institutional and technological change and path dependency, a short description is given of the technology development of the Dutch and Danish wind turbines. Wind energy was boosted by the oil crisis in 1975, and in the 1980s wind turbines were being developed by several actors in several countries. In the Netherlands, wind turbine manufacturers were mostly designing for energy companies, and the government kept its support focus on large turbines. All Dutch wind turbine manufacturers chose the two-bladed wind turbine design, as the cheaper option due to less blades and easier installation, especially for future large wind turbines. In Denmark, a strong

[5]The term co-evolution is originally a term from biology where it relates to the influence the evolution of a species can have on the evolution of another species.

grassroots movements led to mostly entrepreneurs manufacturing a simple, robust model of stall regulated, three bladed turbines. The three-bladed turbines were simpler for reduced vibration problem compared to a two-bladed design. They were more reliable and less noisy, the latter being an advantage for the first customers that were mostly farmers or individuals placing the turbines on their own land. This reliable image of the Danish turbines led to the 'Danish model' as the dominant design. The path-dependency in Dutch choice for a two-bladed turbine made a shift difficult, and in the Netherlands a fall-out of bankrupt manufacturers were a shrill contrast to the consolidation in the Danish wind industry (more in e.g. [243], [249]).

This example shows, that in the trajectory of development of electricity generating wind turbines, the beginning was in a more fluid stage where two-bladed and three-bladed horizontal axis wind turbines were being developed. A more rigid stage with the dominant design of a three bladed horizontal axis wind turbine has been reached, due to technological and institutional influence on the development of the technology. The institutional setting (governmental support, type of customers) and technological aspects (reliability and noise) both had an influence on the success of the local industry in the two countries.

2.3 Multi-actor systems

2.3.1 Micro-founded dynamics

Technological and institutional change have been explained as a (co-)evolutionary process [246] and in any evolutionary process, the dynamics are key (Winter in [46]). The dynamics of an evolutionary process are often described in terms of variation, selection and retention [246]. Out of the variation of new technical innovations and new forms of institutions, a selection is made as to what are the most promising, desirable or acceptable forms. This selection is made not just by engineers, but also by other actors as stated above, e.g. policy makers[6]. Retention refers to the situation where a certain selection choice is preserved[7]. Retention can occur due to technical or physical reasons such as economies of scale, but also institutions can be difficult and costly to establish [246]. E.g. for policy change, laws may have to be adapted, and such changes (especially constitutional changes) can require a long process.

In this selection and retention, one can see that the choices of the actors determine the path. The dynamics can be understood as *micro-founded* by the

[6] In [212], Saviotti states the selection of the optimal technology occurs as an evolutionary process of variation of present technologies and selection therefrom. Dosi [58] states technology development can not be seen as an optimal selection out of a set of given technologies: if so, why would they not have already been developed?

[7] For example, even though the technology of a DVD is more advanced than the video tape, it still took quite some time before the movie DVDs replaced the video tapes in the shops, as many people had not switched from a VCR to a DVD player.

actions of the actors in the related sectors that are involved in the implementation. The actors create the institutional changes and technological innovations, and retain certain institutions and technologies. Coriat and Dosi state *all* evolutionary processes are explicitly micro-founded [46]. In this view, implementation paths can be built up by the actions of actors. Their objectives, interests and expectations guide their behaviour and therefore guide the implementation.

2.3.2 Actors

Actors are defined as social entities: individuals or groups of individuals [95]. Firms, interest groups or governmental organisations all can be considered actors. The delineation and aggregation level of the research determines what or who is exactly considered an actor. For example, the Dutch government can be considered an actor in a study, but a finer level might be required in another study and instead different departments are regarded as separate actors (e.g. the Ministry of Economic Affairs, Agriculture and Innovation), or even finer in Directorates-Generals (e.g. the Directorates-General for Spatial Development and Water Affairs). For the choice of the relevant actors, an actor is a social entity of individuals in between which 'no interpersonal comparison of utility or information transmission is relevant in the relation to the posed problem' [95]. In other words, when actors are the units of analysis, the actor is the smallest social entity one needs to consider for the posed problem without losing detail or information.

Socio-technical systems are multi-actor systems consisting of actors with both private and public interests, creating and subject to market forces and governmental regulations [124]. The involved actors all have an interest or stake in the implementation of offshore wind energy in the Netherlands, as these actors could cooperate towards the 6000 MW target or could inhibit it. Such actors are called the *stakeholders* of the implementation, where the term stakeholder refers to 'an actor with an interest in the subject, where an interest is a certain perceived utility or welfare gained' [98]. Such welfare or utility could for instance be financial gain or ecological preservation.

Other, more strict definitions of stakeholders come from the application of stakeholder analyses[8] for one organisation, where analysts often interpret stakeholders only as parties with a certain power or stockholders to the organisation ([29], [200]). In this study, a broader definition as stated above is used. One can interpret the broader view taken in this study as including a more indirect manner of influence, e.g. via permit consultation procedures. The stakeholders for this study are therefore all individuals and organisations that affect or are affected by the implementation of offshore wind energy in the Netherlands.

[8] In a stakeholder analysis the involved actors and their influence and impact are examined for the impact on the decision making for the organisation [106].

2.3.3 Perspectives of actors

Stakeholders to the implementation of offshore wind parks include governmental agencies and market parties, but also groups and individuals such as interest groups and inhabitants of coastal municipalities. They all have a different perspective on the implementation, as they have a different interest or stake in the implementation: e.g. market parties want to make a profit and environmental groups want assurance that the environmental impact is low. These stakeholders have a varying impact on the implementation, due to e.g. their power, means and resources.

Available resources are allocated by certain actors, according to their strategies and based on their interests and future expectations. The possible implementation speed is influenced by the capacity and state of these resources, as well as time for change for growth and time for production or delivery time. For example, a special-purpose vessel can give a higher installation speed and R&D of the wind turbine manufacturers could increase the capacity factor for onshore or offshore turbines. This does require these actors to decide to invest in these possibilities, by allocating funds for investment or for an R&D budget. Their view on the market will determine if they think their decision will serve their interests. On the other hand, other stakeholders could aim to stagnate the offshore wind implementation, as this implementation does not serve their interests, for instance fisheries as they will not be allowed to fish in the area of an offshore wind park.

Here it is aimed to review the problem from different perspectives, from the perspectives of multiple 'problem owners'. Different perspectives from various stakeholders will be included to assess the impact of the implementation on this variety of stakeholders, instead of viewing the problem from one perspective or one 'problem owner'. One could also state there is no problem owner, as this study will refrain from making judgement in possible conflicts of interests. The implementation paths are made to help gather and explicate different views on the implementation to what is desirable or not and how these stakeholders could affect the implementation speed.

2.3.4 Actors matter

The micro-founded development is a constructionist approach on how implementation paths are created. Such an approach is not new: several approaches have been formulated based in the actions of actors. A few examples will be discussed here.

In the Social Construction Of Technology (SCOT), technological progress is seen as socially constructed, and actors are seen as the system builders([109], [254]). The technology progresses along a multidirectional path with a certain momentum, and is not considered a semi-linear development of alternatives: several trajectories can exist at the same time and it is not necessarily the death of one trajectory leading to the birth of another. A variation of alternatives is reviewed in an interpretative manner by actors as they represent different values to different relevant social groups. Different actors may be considered relevant for different phases of development. Selection is made in phases and backtracking along the trajectory can occur. Eventually closure and consolidation of a trajectory is deemed to occur when a dominant design 'wins'. SCOT does tend to underestimate technology and focus solely on demand-pull [21]. The closure phase seems dependent on the chosen time interval for a study, and does not have to represent the actual closure of a certain technological progress[9].

In Large Technical Systems (LTS), technological progress is also seen as a socially constructed process where actors are the system-builders. In LTS, the systems are reviewed as socio-technical systems, build up from interacting system components consisting of both technical elements (physical artefacts and natural resources), and social elements (organisations and legislative artefacts) [109]. In LTS, the dynamics for technology changes are deemed to follow a loosely defined pattern of phases [109]: invention, development, innovation, transfer, and growth, competition and consolidation. These are comparable to the Schumpeter phases of invention, innovation and diffusion[10] and his ideas of the first phases of a technology being mainly influenced by engineers and entrepreneurs and then going in to a fluid stage where the technology develops a momentum of its own. Hughes describes this pattern of phases as non-sequential: they can overlap and backtrack. LTS does not constitute a full theory [254]: in LTS studies technological progress is described in narratives following the phases.

In *Strategic Niche Management* [199], the focus is on examining and supporting the development of a certain niche technology. The most important aspects are the processes of network formation, voicing and shaping expectations, and learning processes. It is examined how networks of actors are formed, how they learn and what their expectations are. Actor behaviour is therefore of importance: the actions of actors are central. The emphasis is on the networks of actors in the niche.

These examples show that an actor-based approach is used in many theories of technological development. They fit with the notion of socio-technical trajectories and give historical examples of developments of various technologies. They however focus more on solely the social construction instead of describing a co-evolution of technology and institutions. They have a strong emphasis on descriptive methods for an ex-post analysis, explaining the development retrospectively. Here, a future study is endeavoured. The idea is that by building up

[9]For example in the case of the development of bicycles by Bijker [23], the closure phase describes a dominant design, while new alternatives now such as the mountain bike shows that development has not ended. As long as it is in use (is not replaced), the change of a technology does not stop.

[10]Schumpeter also included saturation and decline.

the paths by the actions of actors, taking into account the strategic behaviour of the actors and the opportunities and constraints in which they take action, *a* future view can be created, as above studies do retrospectively.

2.4 Simulation of implementation paths

2.4.1 Defining Implementation paths

The term *implementation path* has been introduced in chapter 1 to denote a path for the implementation of a technology as the physical implementation of technical structures within a certain geographical area. In an implementation path, it is described how the implementation is build up in time: the development of a technology in a certain area is the focus.

The term implementation path has been chosen as a distinction from a *development path*, which refers to the full-cycle development of a technology from a niche technology to a successful adoption of the technology until saturation or decline, see e.g. [194]. An implementation path is defined within a certain time interval or time horizon, and the implemented technology is in a certain stage (or stages) of development as described in a development path. But the focus lies on the actual implementation: the physical realisation. Therefore an implementation path, unlike a development path, does not necessarily start at the beginning of development and does not necessarily end at the saturation or decline of the considered technology.

2.4.2 Implementation as change in a socio-technical system

As stated before, the implementation of a technology takes place within a socio-technical system. In this socio-technical system, both socio-institutional elements and technological elements are present. The implementation path follows a socio-technical trajectory, as long as there is no large disruption leading to a paradigm change. In the previous section it was described that all socio-technical systems are multi-actor systems and the socio-technical trajectory is deemed to be micro-founded by the actions of these actors. Here a framework is presented for the influences and constraints on the actors and their decisions.

Institutional change in a socio-technical system

In [124], Koppenjan and Groenewegen created a four-layer model for institutional analysis in a socio-technical system as an adaptation of the Williamson model presented in table 2.1, see table 2.2[11]. The first and second level in

[11]The presentation of the model has been slightly altered to fit the presentations of other models.

this model are again the informal and formal institutions, the third level represents the institutional arrangements, divided in informal ('unwritten') and formal ('written') arrangements, and level four are the actors and their games, as they strategically take actions towards their own objectives. The frequency of change for these levels is taken similar to Williamson's levels: continuous change in level 4 up to change in 100-1000 years in level 1 (see figure 2.2). Koppenjan and Groenewegen explicitly state all levels are considered interconnected. They describe the mutual influence of the levels: a higher level shapes and constrains a lower level, while a lower level influences the development of the higher levels. Two remarks can be made about the usefulness of applying this framework to the development of the implementation paths.

First, since the implementation path is deemed micro-founded by the actions of actors, an analysis on the fourth level is most crucial for its development. However, higher levels shape and constrain this level: the actions of the actors are shaped and constrained by the informal institutions, formal institutions and the institutional arrangements (which in turn are influenced by the actions of actors). Koppenjan and Groenewegen [124] describe the influence of the institutions of the higher levels on the fourth level. The first level of informal institutions influence the mind-set of the actors. The type of institutions at the second level constrain which actions are (legally) possible. The third level prescribes how transactions on the fourth level are coordinated.

Second, considering the frequency of change for the implementation path within the considered time frame (15 years), the actors can be regarded to be influenced by changing institutional arrangements and placed in a context of formal and informal institutions exhibiting incremental, evolutionary changes. For revolutionary or radical change, also changes in the top two levels can be considered.

Technological change in a socio-technical system

Koppenjan and Groenewegen explicitly state the levels are for the *institutional* analysis of socio-technical systems. For the analysis of a socio-technical system, the analysis of the technical subsystem should be included. The analysis of technical subsystem has also been described as acting on four associated levels by Künneke [125] and Bauer [21], as both use a similarly layered model for the technical subsystem, again grouping into levels based on the frequencies of change and purpose. In [125], Künneke states that different levels of technological practice can be distinguished in different categories with an increasing frequency for change for each lower level. He defines technological practice as the manner in which 'technological artefacts are planned and operated in order to meet human needs'. In [21], Bauer describes the design decisions and emergence in the layered model of the intertwined social and technical subsystems. Based on their work, the layered model for the technical subsystem can be described as follows.

Table 2.2: Four levels of institutional analysis for socio-technical systems, adapted from [124].

• L1	**Informal institutional environment** Informal institutions: e.g. norms, values, orientations, codes.
• L2	**Formal institutional environment** Formal institutions: constitutions, laws and regulations.
• L3	**Formal and informal institutional arrangements** Formal (gentlemen agreements, covenants, contracts, alliances, joint-ventures, mergers) and informal arrangements (rules, codes, norms, orientation, relations).
• L4	**Actors and games** Actor and their interactions aimed at creating and influencing provisions, services and outcomes.

For the technical subsystem, the first level is the level of the technological paradigm, as described by Dosi [58], dealing with tacit conventions as the embeddedness for technologies. Change on this level is decades to a century and represents a paradigm shift: a non-continuous, revolutionary change that occurs in a frequency of about a century, for instance an industrial revolution. The second level is the level of the current technological trajectories, wherein the selection is present for standards and architecture. This trajectory is subject to path-dependency and therefore the changes in this level are more gradual and continuous, and in the order of years to decades. Level 3 is formed by the operational arrangements: routines and protocols governing the operational transactions. Here routines are defined following Nelson and Winter as a 'collection of procedures which, taken together, result in a predictable and specifiable outcome' (as cited in [125]). The last level, level 4, represents the continuous changes to day-to-day operation and management of the technical subsystem, consisting of the operational decisions of actors.

In Koppenjan and Groenewegen [124], the actions of the actors (level 4) are stated to be influenced (shaped and constrained) by the other three levels. Here for the technical subsystem, level 4 again represents the day-to-day actions of actors, although for the technical subsystem the focus lies on the decisions relating to the technical operation. Level 3 concerns the optimisation of the operation of the technical subsystem in scale and scope, and constrain the actions by defining a structure for transactions or in other words, coordinate the transactions between the multiple actors. Level 2 constrains the actions within a certain technological path that has already built up momentum, and the actors are constrained to follow set technical standards. Level 1, the technological paradigm, influences their mindset: the solutions and problem perception. Re-

Table 2.3: Four levels of technological practice in the technical subsystem, as derived from [125] and [21].

	Level	Frequency	Purpose
• L1	**Technological paradigm**	$10^2 - 10^3$	Often non-calculative, spontaneous.
• L2	**Technological trajectories**	$10^1 - 10^2$	Selection of standards and architecture. First order economising: development of coherent and efficient technological systems.
• L3	**Operational arrangements**	$10^0 - 10^1$	Routines and Protocols. Second order economising: Optimisation of individual technical components.
• L4	**Operation and Maintenance**	Continuous	Actual operation management.

lating to the technological paradigm, this mindset forms the types of technical solutions and problems seen by actors in their normal, everyday problem solving behaviour.

2.4.3 Socio-technical systems change within the implementation paths

The implementation paths for offshore wind will be made up to 2020 and the starting point for this study is 2005: this gives a time horizon of 15 years. The foundation of what will be addressed in this study and how, will be presented here using a combination of the above described framework for the analysis of the socio-institutional subsystem based on Koppenjan and Groenewegen, and the framework for the analysis of the technical subsystem (Künneke, Bauer). The analysis of the socio-institutional subsystem has been described above as consisting of four levels: informal institutions and the analysis of technical subsystem is also based on four associated levels. In the previous two sections the levels and their interactions have been described.

It should be noted that the change frequency for these levels of the technical and institutional subsystems are not the same in the level definitions, except for the fourth level of the actors and their strategies (continuous, day-to-day change). However, the influence of the upper levels on the fourth level are of a similar nature for both described subsystems. As level 1 forms the mindset of the actors, the influence of level 1 on level 4 lies on the perceived problems and the solutions available for the actors. Level 2 limits the options available to actors, as they have to comply to formal rules, be they laws or international technical standards. The third level gives coordination to the transactions made

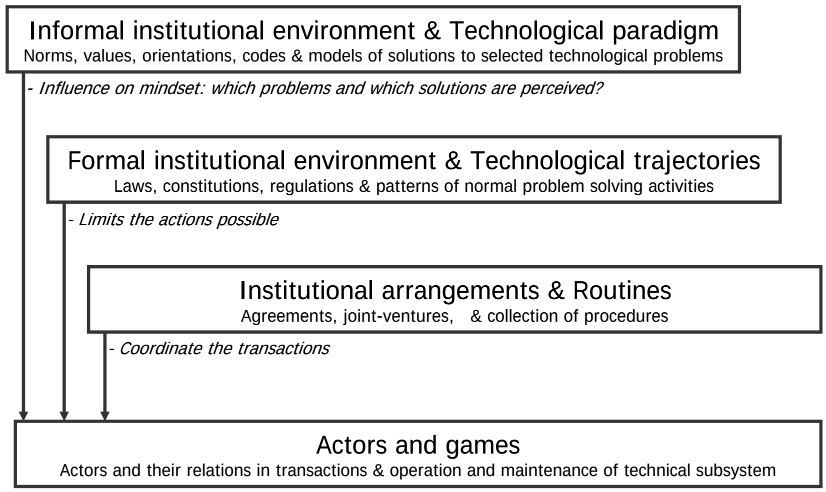


Figure 2.1: Adjusted framework for this study, representing the influence of the upper levels on the fourth level.

in level four. This interrelation of the upper three levels on the fourth level is summarised in figure 2.1. It should be noted that although the influence of a lower level on the development of the higher levels is not regarded *in this study*, this certainly does not mean that this influence is regarded not to exist.

In the simulation, the implementation is build up by the actions of the agents (representing stakeholders), and this level therefore forms the basis for the simulations and define the type of changes mostly seen in the simulation. In short, the simulation should show the actions of actors, using slightly varying protocols (level 3) within a socio-technical environment which is defined for each simulation but might vary between the simulations. As the time horizon is set to 15 years, level three can show some variations in changed routines and protocols. The socio-technical environment (levels 1 and 2) can be considered more fixed, as the frequency of change is much slower. This does not mean that they have to be set the same for all simulations. First, trajectories in the beginning stages are still very fluid and the time for change will be faster than in the consolidation stage. Offshore wind energy is still in this beginning stage, technically and institutionally speaking. Second, especially for level 1 change is slow but its status may be hard to identify. Not all revolutions start with clear indicators of coming revolutionary change such as beheadings.

To illustrate, a short operationalisation is presented for a relevant socio-technical system to clarify the discussed levels. In the socio-technical system concerning the electricity supply, the four levels for institutional analysis and technological practice can be described by the following aspects. On the first level, one can say that the prevailing paradigm is steered to centrally generated electricity. A paradigm shift may occur: distributed generation is receiving more and more attention. This attention is brought about partially because of the shift to sustainable energy sources[12]. This has lead to a variety of (new) trajectories (level 2) for technologies for electricity generation: both the fossil fuel-based, and the sustainable technologies are present in various stages of development. Most of the latter technologies still require institutional changes, as offshore oil and gas extraction had required in the 1950s and 1960s. Such institutional changes consist of the installation of subsidy schemes for financial support and new legislation. For instance the Electricity Act did not yet apply to electricity generation outside of the 12 mile zone in the North Sea when the first offshore wind parks were under development.

In the trajectory for wind energy, the dominant design has become the horizontal axis wind turbine (HAWT), as most series-produced wind turbines are HAWTs. The changes to this dominant design have mainly consisted of methods of optimising the current dominant design (level 3). Upscaling the turbine has been possible by the development of stronger materials, and cost reductions have been achieved by e.g. cheaper production procedures and better aerodynamic efficiency of rotor blades. Technological development will reduce risk and increase the reliability of the turbine, making it easier to close a good Power Purchase Agreement, the agreement between the park operator and the electricity distributors. These distributors have to state their demand and supply of electricity to the National Grid Operator (programme-responsibility). Last, the fourth level actions represent the actions for e.g. operation and maintenance of parks or the national grid, trading electricity, following set maintenance strategies, contracts, legislations and regulations as mentioned above in the upper three levels. These examples are summarised in figure 2.4.

Table 2.4: Operationalisation of the four levels relevant to offshore wind.

	Level	Operationalisation
• L1	Social embeddedment and technological paradigm	Central generation, environmental consciousness.
• L2	Socio-technical trajectories	Fossil and non-fossil sustainable technologies, Electricity Act, removal laws.
• L3	Institutional and operational arrangements	Improvement of blade materials, salvage methods, permit procedures, Program Responsibility, Power Purchase Agreements, maintenance strategies.
• L4	Operation and maintenance	Execution of maintenance, electricity trade.

[12]Brought about by attention environment, geopolitical issues and fossil fuel reserves, see chapter 1

2.4.4 A role-based approach

This study does not aim to analyse certain specific actors or determine how to influence or satisfy specific actors. Instead, it aims to examine how to balance and take into account different perspectives of involved actors. The inclusion of different perspectives on the implementation does not necessarily translate to the relevant real-world actors themselves as the units of analysis for this research. For instance while the perspectives of wind turbine manufacturers will be included in the study, a micro-analysis into the difference between e.g. the Vestas and Siemens company view is outside the scope of this study.

This study focusses on including different 'types' of actors involved. Of interest are the actors' *roles* in the implementation: the parts they play in the implementation. So actors are not considered *per se*, but the parts they play or the roles they fulfil in the implementation are analysed, as well as the perspective fitting to that role. These roles are the functions fulfilled by the actors with the rights, obligations and behaviour patterns[13] consistent with these functions. Such a function can be an active participation to the physical implementation, but it can also be just an involvement in the issue to set conditions to what is acceptable for the implementation (which could be an inhibition of the implementation) based on obligations or certain interests the actor has or represents in this role. The definition of a role is used to emphasise the distinction between the actor and the part it plays in the implementation. An actor can fulfil several roles, and a role can be fulfilled by several actors.

Some examples will be given to clarify this theoretical definition. A project developer has the role to initiate an offshore wind farm and his role is therefore an example of a role that actively supports the physical implementation. A role may be fulfilled by several actors. Greenpeace and Stichting de Noordzee are both environmental groups concerned with the protection of the local marine environment. Alongside this, Greenpeace also has the role for the protection of the global environment, e.g. to fight global warming in their manner. So the two actors, Greenpeace and Stichting de Noordzee, share one role and one of these actors, Greenpeace, also fulfils another role. Both roles are not roles to actively execute the physical implementation, but to set conditions to the implementation. Vertically integrated companies could have different divisions that fulfil several roles[14] , while smaller companies might fulfil only one of these roles.

The focus on roles instead of actors is a simplification of reality. Instead of modelling reality as the collection of companies that can be identified in the real world, reality is modelled as a collection of their roles. The respective views of

[13] Adapted from the definition of a role as used in sociology. A role is considered relatively stable whereas it might be fulfilled by varying actors [260].

[14] This does not always mean it should be regarded as several actors: it may even be one person that is responsible for several tasks, negating relevance for any interpersonal comparison of utility or information transmission, following the definition of an actor in section 2.3.2.

the actors are taken into account by looking at the interests belonging to different roles. Certain aspects are thereby neglected. For instance, the optimism of each specific developer in the offshore wind market in the Netherlands is not investigated. However, the role of project development can have a variable attached to it of 'confidence in the market', as a general representation of real-world actors in this role. An organisation interpreting this study to reflect upon itself can identify with the role(s) in the model that it performs.

2.4.5 Simulating micro-founded implementation paths

Summarising, an implementation path includes a time frame and is part of a complex, multi-actor, socio-technical system. This socio-technical system includes a national setting, including the institutional framework and the geographical setting. Implementation paths are seen as incorporating a part of the socio-technical trajectory of a technology. This is regarded as a co-evolutionary path, as technological change and institutional change goes hand in hands influence each other. Social and technical elements are therefore not regarded in a separate manner, but in an integrated manner as they influence each other.

A constructionist approach will be taken how the paths develop. Implementation paths are seen as micro-founded, build up by the actions of actors involved in the implementation to 6000 MW offshore wind energy in the Netherlands. The decisions made by the actors guide the evolution of a system along a path of technological and institutional change and so the decisions of actors determine the speed and manner of the implementation of offshore wind energy in the Netherlands. By creating possible future implementation paths based on the actions of actors, the paths include the perspectives and interests of different actors. The simulation of socio-technical system follows the dynamics of the fourth level, actors and games, following certain protocols for interaction. A socio-technical context is added as environment, in variations for a comparative analysis.

The approach of this study is to create implementation paths by developing a computer model that will simulate implementation paths (described in chapter 1). This simulation model will be actor-based, or rather role-based: the differentiation of the actors represented in the model is based on their roles. The simulation model will simulate a society of (inter-)acting agents.

Running a simulation is not expected or designed to give *the* implementation path offshore wind energy will follow in the future. The future cannot be predicted, and this study does not aim to hazard a guess. Instead, several implementation paths will be created to span a variety of possible futures to take into account the uncertainty of the future: possible, internally consistent but different paths showing different routes the implementation could follow. The simulation model will also not be designed to optimise or find Pareto equilibria. The values of a rational modelling technique lie in the following aspects [104]: it pushes a modeller to consider an issue from several actor perspectives, it gives insight in the known and unknown variables; and the ‘modelled actor network can facilitate the discussion and decision making’.

3

Methodology

Introduction

The approach chosen in this thesis is to create an agent-based simulation model, to model a complex socio-technical system with the selected actors and factors involved in the implementation. Figure 3.1 depicts in a simplified manner how reality is interpreted in the model. The model consists of interacting agents representing a selection of actors. They are placed in an environment, representing factors that are outside of the control of the agents but influencing them nonetheless: the *external factors*[1]. The environment of the agents will be formed in a consistent manner by the use of scenario planning.

[1] These factors can be seen as influences from other socio-technical systems. This can be related to Freeman's statements on technological systems that are not separate but constellations of innovations, technically and economically interrelated [194]: we state that this should be broadened to constellations of socio-technical systems.

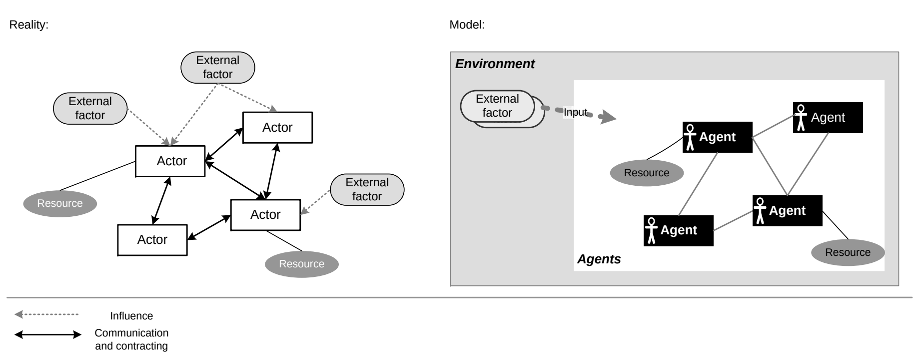


Figure 3.1: Basic system representation showing the modelling of actors as agents and environmental scenarios depicting the environment.

This chapter will introduce the methodology of this thesis, as the identified steps for the development of the agent-based model of the implementation of offshore wind in the Netherlands. Its main components, agent-based modelling and scenario planning, will be explained. First, in section 3.1 an introduction will be given for agent-based modelling (ABM), explaining what an agent is and how ABM can be applied. Second, scenario planning will be introduced in section 3.2, explaining how it can be used to create environmental input scenarios. Third, the methodology of this research is explained in section 3.3, describing how both agent-based modelling and scenario planning are combined for the development of a model to create implementation paths for offshore wind energy.

3.1 Agent Based Modelling

3.1.1 Introduction

In social science, computer simulation gathers momentum as the 'third way' of doing social science, after induction and deduction ([93], [15]). Social science studies human society and social interaction and several modelling techniques are now used to simulate these; for instance dynamic systems, cellular automata or micro-simulation (e.g. [219], [136]). To model actors, with a certain behaviour, agent-based modelling (ABM) has become increasingly popular. Because ABM offers the possibility to model actors in an environment acting according to their own rules, it is a promising modelling technique for this research.

First the definition of an agent is discussed, in both functional and technical sense, second the application of ABM is discussed, both as used in the social sciences in general and then in this thesis in particular.

3.1.2 An Agent

An agent has many definitions depending on the field of application. In computer science, there are two main fields of application for agents: agent-oriented software engineering (AOSE) and ABM. In the first, AOSE, an agent approach is applied to create a product, a computer program or system, and agents represent functionalities of this product. In the second, ABM, agents are used to create a model for simulation of a complex system[2].

An agent in the functional sense

In both AOSE and ABM, there are characteristics of an agent that are agreed upon, even though what the agents represent is different. An often used definition of an agent is the definition of [116] that states:

[2]In this use of the term agent one can see a similarity with its use in economics, where an agent refers to an actor as a decision maker.

> An agent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives.

This definition is basically a summation of the characteristics that an agent should have. First, the *encapsulated computer system* means that an agent is an identifiable separate computer program with its own characteristics and rules governing its behaviour [134]. It has some degree of control over its own state and the execution of its methods. Second, they are *situated* in an environment with other agents. In this environment they are *reactive*, meaning that they can perceive information from their environment and respond to it, and *communicative*, meaning they can communicate and interact with the other agents. Third and fourth, the agents can take *autonomous* and *flexible* action. They are independent and they can act without intervention; no-one determines its actions to steer the agent to its own objectives. They can learn to adapt their behaviour[3]. Fifth, agents have their own objectives and their actions are goal-directed towards these objectives. Agents are not just reactive, but also *pro-active*: they can take initiative for action based on what they think will help them towards their objectives (goal-directed behaviour) ([270], [116]).

An agent in the technical sense

Some elements of the above definition may remind the reader of objects in Object-Oriented programming. This is no coincidence, and because of their similarities Object-oriented programming languages are very suitable for programming agents. Agent-based models are therefore often programmed in OOP languages. But there are differences between an agent and a 'normal' object as they are used as programming concepts.

Many engineering students had their introduction into computer programming in procedure-oriented programming languages such as Pascal. In procedure-oriented programming, a problem is divided into a sequence of operations, where a frequently used sequence can be grouped as a procedure for re-use. The program executes and in its flow of execution it addresses its procedures to finish the task. Procedures can then be called (several times) by the `main` or other procedures. In object-oriented programming (OOP) a problem is divided into concepts, coded as *objects*. Objects are encapsulated programs, meaning they are self-contained: an object has its own properties, internal data structures and logic and is not dependent on code outside of his own scope. It may however use other objects. So objects are incorporated on a functional level, instead of at a technical level as procedures are in procedure-oriented programming: their use requires no specific knowledge of their coding[4]. A programmer has to know an object's use, its required input and expected output, but he can consider

[3] It is still a point of discussion if this is a basic characteristic [134]

[4] An object may even be written in a programming language unknown to the programmer that uses it.

its internal workings as a black box. This way of programming is getting more popular as it is easier to use other programmer's code and build and maintain large programs. It does require a different way of thinking about programming; one can truly speak of a paradigm shift in computer programming. Examples of OOP languages are Java or C++.

In object-oriented programming, a functionality became an Object, or in other words it 'got its own room': there still is a main flow of execution that control the Objects, by addressing their methods. Reusability is key and even though procedures are now Objects they are still considered only to perform the actions (indirectly) as intended in the main flow of execution and exactly in the way the `main` intended. This initiation of an object action can directly come from the `main`, or indirectly through another object who was assigned by the `main` (and so on).

In agent-oriented programming, agents really 'move out on their own', as the actions of an agent are not just the execution of an assignment of the main program but it decides for itself what it wishes to do with a request from the main whilst communicating with other agents[5]. McBurney [140] states the different between an agent and an object as:

> ..., software objects are fixed, always execute when invoked, always execute as predicted, and have static relationships with one another. Software agents are dynamic, are requested (not invoked), may not necessarily execute when requested, may not execute as predicted, and may not have fixed relationships with one another.

Gasser [86] states that the main attributes of agents are their containment of knowledge, their sense of their environment and their ability to perform actions. This definition does not make clear how ABM is different from OOP, since an object and an agent are both encapsulated systems that hold knowledge, sense their environment and perform actions. Agents are specifically autonomous; they can act without intervention, no-one determines its actions to steer the agent to its own objectives. Although objects get input from an environment and they can combine this input with their own 'knowledge' to decide an action, objects are not autonomous. Their methods are simply (indirectly) called by the `main` and they execute as invoked by the `main`. Objects take no initiative for action, while agents do.

3.1.3 An agent-based model

One of the first applications of agent-oriented programming was in Artificial Intelligence; the agent-oriented programming approach started from Distribu-

[5]To compare this distinction of an agent and an Object with the economic notion of an agent: in [38], Batt is quoted: "that which distinguishes an agent from a servant ... [is] the freedom with which an agent may carry out his employment". In agent-based programming the agent works towards its own objectives, but chooses its methods how to achieve them.

ted Artificial Intelligence (DAI) systems, where a groups of agents cooperate to solve a problem [271]. One can understand why the agent-Oriented approach and the 'self-thinking agents' would spark the interest of social scientists, leading to agent-based modelling: an agent-based approach offers a possibility to simulate a social system by modelling individuals or organisations and their behaviour and interaction, and can therefore form a clear representation of several interacting actors (individuals or organisations) to model social phenomena [93]. As Brown states in [28]:

> Agent-Based Models are computer representations of systems that are comprised of multiple, interacting actors (i.e. agents)[6].

An Agent-Based model (ABm) is formed by two parts: agents and their shared environment. A model consists of several agents and their specified relations, where agents are communicating, cooperating and working towards their (sometimes common) goals, situated in a certain environment. This situatedness in a certain environment is an important factor. This environment is *uncertain*, where Padgham [191] divides this uncertainty by naming the environment as *unpredictable* and *unreliable*: the agents cannot predict the state of the environment in the future, neither can they rely on their actions having the desired effect on the environment. The agents have behavioural rules, to decide which actions they should and can take.

For clarity, it is emphasised that the following abbreviations are used: ABM stands for Agent-based modelling and ABm stands for an Agent-based model.

3.1.4 An example

One of the first agent-based models is Schelling's segregation model from 1971 (e.g. [134], [136])[7]. Cellular automata had been in some use: cells on a two-dimensional grid constituting a model, where each cell is in a certain state depending on the state of its neighbours[8]. In Schelling's model, the cells became autonomous agents in a shared environment, taking action according to their objectives. These agents are one of two colours and were placed scattered over a two-dimensional grid. They can see the colours of their eight neighbours, their so-called 'Moore-neighbourhood'. They are given a slight preference not to become a minority in their area: if less then three neighbours are of the same colour, they will move to a new location on the grid that does meet that desire. The simulation starts with the agents in a random initial position. During the simulation, groups of one colour start to clot together, and it often leads to a completely colour-segregated grid. Even when agents had only a small preference to live with their own colour or, in other words, were only mildly racist,

[6] Last remark added by Jennings [116].

[7] However, Schelling himself played his game on a chessboard instead of on a computer.

[8] The main differences between cellular automata and agents are that agents do not have to be defined on a grid, do not have to move at the same time and are more complex in their decision to act and interact.

segregation arose.

Schelling's model shows how a system can be built up using a bottom-up approach, by defining the elements of the system, so at 'micro level'. The behaviour of the system (at 'macro level') arising from the (inter-)actions at micro-level can be surprising, such as the possible complete segregation arising from only a slight preference to live close to your own colour in Schelling's segregation model. Such macro-level system behaviour arising from the micro-level behaviour is defined as *emergent* behaviour.

3.1.5 Applications of agent-based models

There are basically two different applications of ABM in social sciences: modelling an experimental set-up or modelling a part of the real world. In both applications, agents' behaviour is restricted by a rule set. Such a rule set can be completely devised offline or certain rules may emerge from within the system [272] [9]. This rule set can portray certain socio-institutional or technical restrictions of the reality one is trying to capture in the ABm. The socio-institutional restrictions are the institutions, the rules of the game, as explained in chapter 2: formal institutions, informal institutions and institutional arrangements such as cultural beliefs, laws and market rules. The technical restrictions can be for instance be physical conservation laws or a restriction on the weight an agent can carry.

In an experimental set-up, agents represent strongly simplified individuals or simple decision makers following a certain set of rules and strategies in a simple environment, for instance a 2D space. Agents are numerous and homogenous, in the sense that they all have the same set of behavioural rules and objective design. Usually a convergent state of the system is searched for after a certain number of interactions between the large number of agents. Here ABM is not used to model a situation or development in the real world but to test a certain idea or concept.

When modelling a part of the real world, agents are usually heterogenous as they represent different kinds of actors with different objectives. Here the focus lies on the influence of the input of a (more complex) environment, the rules governing the agents' behaviour and the interaction with other agents. The ABm is used to study the interaction rather than some converged state. To explain both the concept of an experimental ABm and real-world modelling, two examples are given: an experimental set-up is explained in Example 1, real-world modelling is exemplified by Example 2.

[9] Offline design of social rules for agents is closely related to mechanism design, where one wants to devise rules in such a way that system results in desired outcome even though individual agents are self-interested [101].

Example 1: Convergence and search costs

In [262], an ABm is presented where simple agents trade with each other in a certain network structure. In the simulations, 500 agents are used, all with the same goal to achieve an equal division in two tradable goods within its own private collection. All agents start out with only one type of commodity and an agent searches for a trade partner among the agents it can communicate with. The agent that offers it the lowest price is chosen and the transaction is made.

The network is formed by dividing the 500 agents into several clusters. Four types of networks of communicating Agents are examined. In the first configuration, all agents are able to trade with all other agents. In the second network, the agents are divided into 5 clusters of 100 agents each. In the third configuration, again the agents are divided into 5 clusters of equal size but in each cluster there are two agents that can trade with one agent of another cluster. The last network shows basically the same configuration as the third but now in four groups there is an agent communicating with an agent from another group. In figure 3.2, these group formations and communication lines are depicted in a simplified manner.

For these four different networks, Wilhite examined the search costs and the number of trades required for price convergence. As price is set determined on an agent's personal balance of the collection of two tradable goods, price convergence shows a good, equal division of the commodities. The search cost is the total number of agent communications of price offers. The results (listed in Table 3.1) show that although in the everybody-talks-to-everybody configuration convergence to a common price is achieved in a smaller amount of trades, it took many more searches to achieve. As a search will also have a certain transaction cost[10] (e.g. the cost of communication to retrieve the price information), the first network is not considered the cheapest network. In a simplified manner, one can see the configuration of global communication: should everyone be connected or can certain agents in a group make sure a fair division of goods is achieved for the entire cluster they are in[11].

Example 2: Multi-Agent model of the UK electricity market

Several ABm's have been developed to simulate electricity markets, see e.g. [19], [32], [65]. Such models can be used as electronic laboratories, to test regulatory structures before they are applied in real systems [174]. Here one of these

[10] Transaction costs are the costs associated with a(n economic) transaction, e.g. information cost. These costs were first described by Coase [38] to explain the existence of firms and integration.

[11] And, more along the lines of firms and transaction costs, does the agent communicating with another cluster profit from this, or does he suffer higher information costs for the good of the rest of his cluster? The paper [262] does not go into individual agents, however.

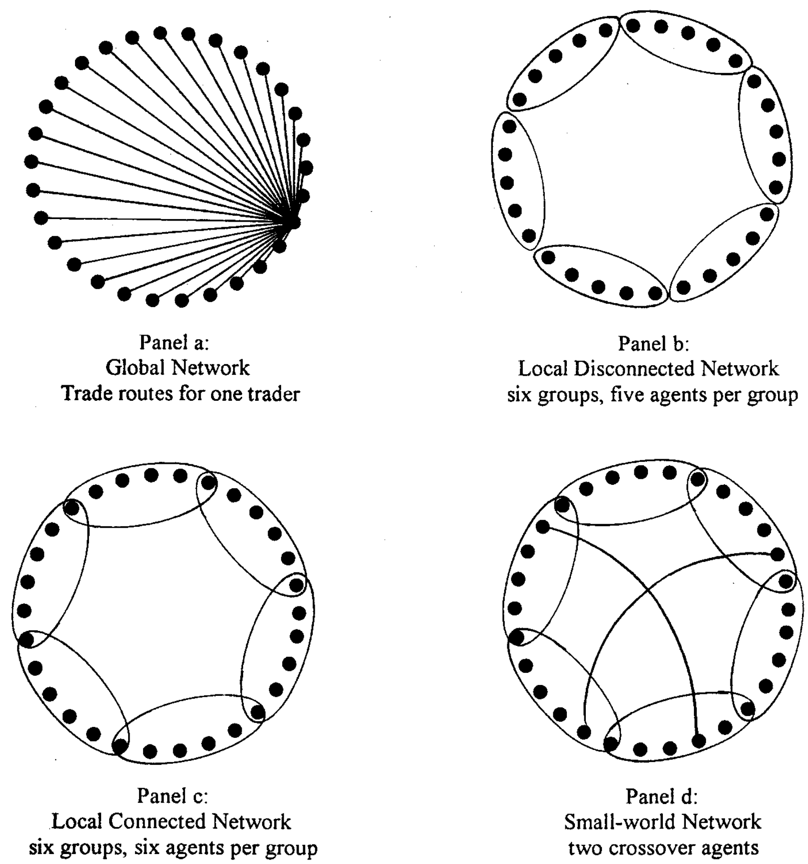


Figure 3.2: Example 1, Simplified depiction of the four configurations of clusters in network. The graphs show the connection between the clusters, but for a total of only 5 Agents per cluster. The simulations were run with a number of 100 Agents per cluster. *Source: [262]*

Table 3.1: Average equilibrium characteristics, as a calculated average over 50 simulations for every network configuration. *Source: [262]*

	Prices (SD)	Rounds	Total trades	Total searches
Global network	1.0046 (0.00168)	8.08	1953.38	2015960
Local disconnected network	1.0396 (0.2771)	7.02	1727.7	31590
Local connected network	1.0048 (0.0146)	497.14	93975.72	2734270
Small-world network	1.0045 (0.00724)	242.54	45944.56	1236954

models is discussed as an example of real-world modelling using ABM: models simulating the New Electricity Trading Arrangements (NETA) in England and Wales.

In 2001, the NETA replaced the daily uniform price auction with a system of continuous bilateral trading up to gate closure 3.5 hours ahead of real time in England and Wales. To test this new market structure, Bunn and Oliveira created an agent-based model as a stylised model of the electricity market of England and Wales using the new arrangements of NETA. The model includes three types of agents: generators employing their units, suppliers buying to suit their demand and a system operator balancing the system.

The electricity is bought and sold in two interaction schemes: the Power Exchange and the Balancing Mechanism. The Power Exchange is a bilateral market, modelled by a single call auction[12]. The Balancing Mechanism works as a market as well, as the system operator buys and sells increments and decrements to balance the system. Individual generators and suppliers may still be out of balance: if a generator generated too much or a supplier overestimated its demand, an imbalance of spillage occurs; when a generator generated less or a supplier consumed more than it had contracted, an imbalance of top-up occurs. If an agent (a generator or supplier) causes spillage, it receives the System Sell Price for the electricity, if an agent (a generator or supplier) causes top-up, it has to pay the System Buy Price. By ensuring the System Buy Price is higher than the System Sell Price, the incentive is created not to be out of balance. The generators have different generation technologies. The generator units have parameters associated with their technologies, e.g. fitting marginal costs, start-up costs and no-load costs[13]. All plants can be used a maximum number of times per day defined as the maximum amount of cycles, and baseload plants have either no or a single cycle. All agents maximise their profit and can learn from their history and change strategy, for instance the choice of which market (the Power Exchange or Balancing Mechanism) to buy or sell in.

Worried about possible market abuse by generators, the market regulator Ofgem wanted them to sign a 'market abuse license condition' which should act as a good behaviour clause. Two companies, British Energy (BE) and AES, refused to sign the condition, stating that it was not necessary as they alone could not influence market price. AES is a small generator company with less than 10 % market share, while BE had more than 10 % market share but mainly baseload (nuclear) generation. Bunn and Loiveira tested this in their electricity market agent model [33]. They concluded that BE could influence the prices in the power exchange and AES (alone) could not, whereas neither could significantly influence the prices in the balancing mechanism. Only when they worked

[12] The agents in the model do not communicate directly, and it was therefore not possible to use a continuous double auction [33].

[13] Not all defining parameters are taken along, for instance ramp rates are not taken into account.

together could either of them significantly profit from the capacity and price manipulation. This fits with the decision of the Competition Commission, who decided that the Competition law was a sufficient (and less awkward) regulatory instrument to ensure the proper functioning of the market.

ABM in the examples

In the first example, one can see that the agents are simple decision makers. Their behaviour can be captured by only a few behavioural rules: they set a price at which they will trade and they can send each other messages to make a trade. With the example, Wilhite wishes to examine a certain topic, and does so in an experimental set-up taking along only the trading behaviour. In the second example, the agent is modelled more along the lines of an actor and the model more represents reality, albeit a simplified one. Of course, ABms can be made somewhere between very simplified to very detailed: the examples give an indication of how broad the type of ABms can be.

3.1.6 Agent-based simulation of complex systems

For a complex system, one cannot evaluate the change in the entire system by cutting the system into pieces and evaluating these pieces separately. Gilbert ([92]) emphasises this as:

> ...human societies, institutions and organisations are complex systems, using 'complex' in the technical sense to mean that the behaviour of the system cannot be determined by partitioning it and understanding the behaviour of each of the parts separately.

One has to have understanding over the smaller pieces *and* their interactions, in order to simulate and evaluate a socio-technical system without having to oversee the system in its entirety ([15]). Thus Agent-based modelling could make modelling of complex social systems possible if its parts and interactions can be designed and combined in a model which then gives results over the entire system represented by the model. This opens an opportunity to simulate social phenomena or analyse imaginary societies. In a more experimental way, artificial situations or a specific setting can be analysed or reproduced ([15], [116]).

Schelling's segregation model showed how an interacting combination of parts can yield surprising results for the whole system that were not previously foreseen because of the complexity and lack of oversight over the entire system, the *emergent behaviour*. Emergent behaviour can make verification an validation of an ABm more difficult. One is looking for surprises, to find aspects of the system that have not been considered yet because of its complexity. Although surprising results may be interesting, first one will have to find out whether these results are due to an error or to emergent behaviour. To help with the verification, runs can be made where certain results can be expected, whether because of simplicity in the chosen variables or because of gathered data. This makes checking for errors easier, as according to e.g. Jennings [116] and Gilbert [93]).

It should be noted that possible errors could come from a programming error, but could also originate from the way the agents are modelled. In the creation of an agent based model, four different roles can be identified ([85], [62]). The analyst or domain expert interprets the problem and creates the domain model. The modeller simplifies reality into a conceptual model or design model. The computer scientist designs the operational model and the programmer implements the operational model. Errors can be made by all roles during the process[14]. For analyst's or modeller's errors, correction and validation can be hard because there is often a lack of data or knowledge of the socio-technical system one is trying to model [85].

The question whether social phenomenon can be represented as agent-based models then becomes whether the unit of analysis for social science can be modelled in a satisfactory way for the research question to be answered. The units of societies 'vary greatly in their capabilities, desires, needs and knowledge' and societies are in constant change [92]. One condition for using ABM could therefore be that one should be able to describe the behaviour and decision making [135]) in a manner that can be captured in algorithms. When using ABM one should not forget that one cannot get out what is not put in: if it is not included in the modelling variables, it will not magically appear. In the words of Wooldridge ([272]):

> Agents are ultimately just software, and agent solutions are subject to the same fundamental limitations as more conventional software solutions.

3.1.7 When to use agent-based modelling

In general, ABM offers a method for macro-level analysis by micro-level modelling, as the system is built up from the bottom up. The advantages of this approach have been mentioned in the previous section: it can capture emergent behaviour and one can model 'as-is'. A third main aspect is the flexibility of an ABm [24]: the ABm can be extended or adapted by adding more agents or changing the behaviour of the agents, allowing the model to be scaled up to arbitrary size [135]. With these aspects in mind, one can begin to see when ABM could be a useful technique. Following the advantages put forward, it can be beneficial to use ABM when the model needs to be flexible, or when agents can offer a natural representation of the real world.

[14] These roles can be fulfilled by four different persons or less: e.g. the last two roles or all roles might be combined.

In literature, other cases are mentioned when choosing ABM could be beneficial. Janssen and Ostrom describe several approaches to using empirical data (stylised facts, case studies, laboratory experiments or gaming) and describe how agent-based simulation can be used to explain data, for instance to confirm macro-level patterns under certain conditions [114]. When on the other hand one wishes to explore possible futures[15] one has no data to compare to. ABM could be used to examine the macro-level patterns from the bottom-up in these cases where 'the past gives no prediction for future' [135]. Axtell [18] describes the use of ABM solely from a computational point of view in comparison to analytical methods, and gives examples when ABM should be preferred: when analytical calculation is possible but numerical realisation is easier; when a problem can only be incompletely solved or when mathematical modelling is intractable; or probably insoluble. If mathematical modelling is intractable or insoluble it can be due to the complexity of the system under review and the internal behaviours, relationships or environment: the characteristics of the described world itself can hint at when thinking in agents can be advantageous.

When the actors to be modelled are heterogeneous, meaning they have different goals and behaviour, ABM could be useful as several types of agents can be modelled and combined. Their behaviour can be non-linear and discontinuous as their actions can change once a certain threshold is reached: ABM can incorporate this. The use of agents could be useful when the agents' behaviour is adaptive, for instance when they learn from experience. Macro-level (process) approaches using mathematical modelling, such as dynamical systems, will get complex fast if equations have to capture all these different actors and changing behaviours.

When the interactions between the actors are not fixed but dynamically changing [135], thinking in agents can be helpful. When modelling a society, the topology of interactions can be called complex [24] when the interactions are heterogenous and non-linear. ABM can handle such a changing, complex topology. Compare this for instance to dynamical system modelling, where the model is based on the average behaviour of the system to form the equations, but this global behaviour cannot capture network effects or other changes to interactions [24].

The environment can also hint at a useful application of ABM if the spatial aspect is important, for instance for modelling on a 2D grid ([24], [135]). Also, when the environment is uncertain and changing, one might want to use an ABm.

Summarising, it has been stated (in e.g. [24], [135], [114]) that the application of ABM could be useful when:

[15] As we wish to do in this study.

- one wants to analyse the macro-level from micro level interactions (the process is considered a result of the model, not an input to the model),
- it offers a natural representation, a natural metaphor of modelling 'as is' in the real world.
- actors are heterogenous,
- actors have complex behaviour, e.g. discontinuous, non-linear,
- actors can adapt their behaviour, e.g. learning,
- relations are complex: heterogeneous, adaptive and changing,
- qualitative and quantitative data needs to be combined,
- the past is no predictor for the future.

However, it has to be taken into account that:

- The results are dependent on the fit of the representation of an actor as an agent.
- The results are dependent on the delineation.
- The results can be difficult to validate.

3.1.8 Methodologies for ABM

To help the agent-based modeller, methodologies and toolkits have been devised. The methodologies are sets of procedures to analyse and design an ABm. Toolkits are a set of software libraries as a basic software building blocks for use when implementing a program. Toolkits usually do not include a model structure, but can give a design structure how to organise the implementation of the model. Toolkits will be discussed in section 3.1.9.

Agent methodologies should give procedures how to divide a system into different pieces to be represented by the agents, followed by concepts on the design of these agents. To use agent-based modelling in the social sciences, literature gives a collection of methods and techniques useful in creating ABm's, rather than offering complete methodologies. Although it is true that all ABm's are unique, certain parts of the creation process can be identified as necessary or convenient for all AB models [203]. In [134], Macal states that ABM is not unlike other simulation techniques: the purpose of the model has to be identified and the system has to be systematically analysed to determine all its components and their interactions. He adds that there are however some tasks specific to ABM:

1. Identify the agents and get a theory of agent behaviour,

2. Identify the agent relationships and get a theory of agent interaction,
3. Get an ABM simulation platform(s) and an ABM simulation model development strategy,
4. Get the requisite agent-related data,
5. Validate the agent behaviour models (in addition to the validation of the entire model),
6. Run the model and analyse the output from the standpoint of linking the micro-scale behaviours of the agents to the macro-scale behaviour of the system.

There are fairly complete methodologies to create *agent-oriented* software. The difference between agent-oriented and agent-based programming lies in what the model and the agents represent. In agent-oriented software engineering, the agent represents a functionality, not (a stylised version of) an actor in a society. An example of such an agent-oriented user program is a program of an online bookstore where agents represent functionalities such as stock-keeping [191]. In agent-based modelling, the analysis phase will differ from agent-oriented systems methodologies considerably. As the ABm tries to capture a part of reality, in an analysis phase this reality needs to be examined before one can turn to decide which 'functionalities' should be included in the model. For the analysis phase, an actor-factor analysis should therefore be added in the methodology to explore and delineate the system to be simulated. The AO methodologies can however partly be used for the development of (a methodology for) ABm's, especially in adapted terminology and used diagrams. For the methodology of this thesis, presented in section 3.3, elements have been used of AO methodologies, especially Prometheus.

Examples of agent-oriented (AO) methodologies are Tropos, GAIA, O-MASE and Prometheus. In Tropos, actors from the application domain are identified as a step in the methodology [27], but these actors are the users of the end-product, the software program. GAIA separates the development in an analysis phase and a design phase, but it does not include an implementation phase ([273], [272]). Prometheus was developed as an agent-oriented methodology for non-experts, with an aim to offer a complete and detailed description of the necessary steps to building an agent-oriented system ([267], [191], [192]). It includes a number of system models and their notations for the three phases of making the system. The methodology uses UML(-like) symbol diagrams often originated from object-oriented programming methodologies. The most important diagram is the system overview diagram, showing all steps in all phases. The three main phases identified in the Prometheus methodology are:

1. *System specification phase:* The goals of the system are identified and translated into functionalities. Several *use case scenarios* are made as a

sequence of steps of the system in operation; they give examples of how the system could be used.

2. *Architectural design phase:* Agent types are made by grouping functionalities. Tools that aid the determination of the grouping of the functionalities are the Data Coupling Diagram, examining which functionalities require which data; and the Agent Acquaintance Diagram, showing which agent interacts with which other agent. Information from the environment is called *percepts* and information or requests from other agents are called *messages*. The overall system structure is presented in a System Overview Diagram. Next, the interactions between the agents are described using Interaction Diagrams. These Interaction Diagrams are developed using the use case scenarios of the previous phase. The Interaction Diagrams are presented in UML sequence diagrams. Following this step, the interactions are fully specified in the interaction protocols. These interaction protocols list all messages and percepts an agents could receive.

3. *Detailed design phase:* For each agent, an agent overview diagram is made of all internal actions within the agent. The agent's capability or capabilities are identified (often following the functionalities that were grouped in the agent) and further developed as plans, beliefs and events.

An overview of the methodology is given in figure 3.3, taken from [192].

Even though Prometheus has been developed for agent-oriented systems instead of agent-based models, elements of the methodology are useful when developing an ABm. The interaction diagrams and protocols are a useful tool to depict the interaction between agents representing social actors just as much as agents representing functionalities in a software system. These protocols defining the interaction between agents can also be seen in the GAIA methodology.

ABM is a fast developing modelling paradigm and it should be noted that recent work has been published that addresses the conceptualisation and methodology for the development of agent-based models. Ghorbani [91] uses Ostrom's Institutional Analysis and Development framework to define a conceptualisation framework for agent-based social simulation. In this framework, informal and formal institutions are incorporated in simulation models as separate objects called norms and rules. In [51], an extensive methodology for agent-based modelling of socio-technical systems is presented, together with several case studies illustrating the methodology. Their ten-step methodology addresses the actor identification that is not addressed in above mentioned methodologies. It starts from actor and system identification, going to concept formalisation and model formalisation (using pseudo-code) and the software implementation. Actor and system identification is performed by brainstorm sessions, interviews and literature reviews to identify different actors and actions that should be included. It does not address actor behaviour specifically, nor does it include interaction protocols as a sequence of actions as is included in e.g. Prometheus. It does

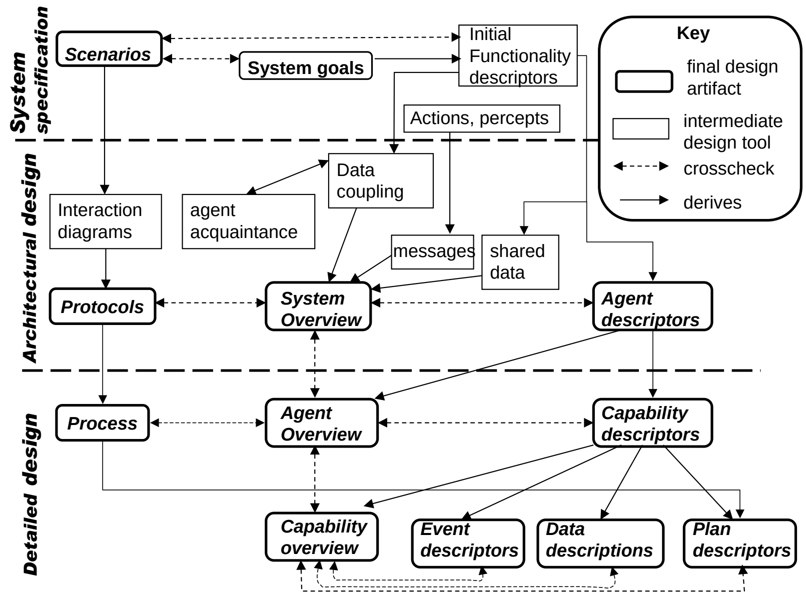


Figure 3.3: Overview of the Prometheus methodology

include model verification and validation guidelines as to what type of runs can be made for verification and validation.

3.1.9 Use and selection of an AB toolkit

There are several functionalities required by all or most agent-based models, for instance scheduling the actions of Agents, graphical procedures and handling statistical output. A toolkit can offer a library of such procedures. Apart from these libraries, some toolkits offer a model structure and conceptual framework for designing ABm's. So using a toolkit can have advantages in developing (i.e. programming) the ABm.

There are several simulation toolkits available[16] that offer designing and developing ease to ABM programmers in a varying degree. Of these, the most well-known are SWARM, Repast and NetLogo ([231], [202], [162]). For the choice of a toolkit for this research, two criteria were set. First, the toolkit had to have been designed for use in the social sciences. Second, it had to be accessible for a new practitioner in ABM. The last criterion implies that it has to be based on an object-oriented programming language that is relatively easy to learn.

[16]Most of them are freeware

Repast J ('Repast for Java') was chosen as the toolkit for this research, see e.g. ([202], [41], [234], [175]). It is often seen in literature as the most accessible, stable and extensive toolkit directed to the social sciences ([198], [237], [234], [163]). Repast offers scheduling of the actions of Agents, a Graphical User Interface and the possibility for batch runs. Java is a relatively easy programming language to learn[17], with many libraries available and the possible use of Eclipse. The integrated development environment (IDE) Eclipse is a user-friendly IDE for programming in Java and offers easy connection to a repository[18].

Its downside is that it does not offer a fixed framework and the extensive packages in the Repast libraries are not easy to sort through ([198]). Repast J does not offer methods for statistical data output, but other toolkits lack in this part as well [198]. There are tutorials available for first-time users of Repast J to get acquainted with Repast's basic features, e.g. the tutorial CarryDropModel by John Murphy [156]. In appendix A the basic shape of a Repast J based model is given.

3.2 Scenario planning

3.2.1 Introduction

The use of the word 'scenario' for a realistically plausible future comes from Herman Kahn in his work for the US Department of Defense in the 1950s [39]. Scenarios were first developed and used in a business environment by Shell to guide business strategy ([103], [216]). In storylines, future oil prices were examined to support investment decisions. In the very beginning of the 1970s, a scenario by Pierre Wack showed a possible future with high oil prices, a situation not thought realistic before the oil crisis in 1973. What Pierre Wack had done was look at the location of the reserves and the attitude of these countries. At the time, the OPEC countries were not happy about the support for Israel by Western countries ([216], [263]). This line of thought led him to the possibility of an oil embargo, with lower production and an increased price. At first the managers in Shell did not think this likely and did not incorporate the scenario in their every day planning, but when the oil crisis hit, they could react faster because of the scenario had described the consequences of such a situation. After the two oil crises, the return of low oil prices was almost unthinkable in people's mindset after 10 years of high prices. Shell was contemplating the start of the Troll oil field, an expensive field as the field was offshore in deep waters. Their scenarios showed that if the relations between Russia and the NATO countries

[17] Java has some advantages over C++, for instance the Java garbage collector automatically kills instances after use ([128]), helping the programmer use the memory efficiently.

[18] For the model developed in this thesis, use was made of the repository of the EI section at TPM. Since the remote repository makes downloading and committing changes easy from any location with a connection to the Internet, the author is grateful to the EI section at TPM and especially Igor Nikolic.

would improve, the availability of Russian oil would deflate the oil prices [56]. They decided to look at bringing down the price of extraction at Troll, and not invest in buying other oil fields as prices were very high. In 1985, the oil price fell, and Shell bought new oil fields at half the price of the year before [216].

The Shell scenarios anticipated future changes that were considered unlikely at the present time, but were not impossible. They had helped Shell to react faster to future changes and hedge their risk in decision making according to several future images. This Shell story introduces scenarios and their use. Scenarios are views of the future, where the emphasis lies on scenarios not as forecasts or predictions, as the future cannot be predicted. One quote of Porter is a very broad definition under which most uses of scenarios can be understood [84]:

> A scenario is an internally consistent view of what the future might turn out to be - not a forecast, but one possible future outcome.

Although one scenario can be used as a storyline to illustrate a forecast or structure a discussion, a single scenario creates only a single vision. Usually several scenarios are made to show the range of possible futures [141]. Instead of trying to predict the future, a range of scenarios span the future [216] and show the uncertainties the future holds and their impact on a certain issue. In this way, scenarios are a vehicle to help see the ramifications of decisions in the future.

3.2.2 Application of scenarios

Scenarios can support the decision making process in several ways. Scenarios can be used to test the possible results of several business strategies in different future environments, where a strategy is robust if it performs well under all scenarios. This use of scenarios is also called 'wind tunnel testing' [206]. A baseline scenario can be used as a scenario if no action is taken to test how desirable another scenario, in which a strategy is tested, is compared to this baseline. Scenarios can also be used as communication tool, to spark debate or to create consensus, for instance over a future vision ([103], [102]). They can also be of use to show the possible results of the choice of a certain strategy, for instance a 'maximise profit' strategy or a 'least regret' strategy.

Three categories can be distinguished, where the choice depends on *how* scenarios are to be used in the decision making process: policy scenarios, strategic scenarios and environmental scenarios [69]. In *policy scenarios*, scenarios are formed around different policy choices in a chosen environment, whereas *strategic* scenarios combine policy choices in several different environments. In *environmental scenarios*, only the changes in the environment form the scenarios. The Shell example above were environmental scenarios. The environment is formed by the external factors, which refer to the possible changes over which one (e.g. the company) has no control. This environment is also called the surroundings or the contextual environment [103] of a company. This last category, the environmental scenarios, is the most prevalent category in business applications. They help to deal with or spot new environmental pressures, political and economic changes, and industry structure changes [216].

A distinction can also be made in *descriptive* and *normative* scenarios. Descriptive scenarios start from the present and go to a future view by examining driving forces and trends, and exploring the possible changes by asking "What if?". Normative scenarios are oriented towards a certain desired future: these scenarios consider actions to be taken in the path to a certain future objective. It is then examined how this 'ideal world' could be achieved by backcasting techniques [197]. An example of a normative scenario is Wind Force 12 [73], in which 12 % of the world's electricity demand is produced by wind power, based on required annual growth rates, progress ratios for the industry and wind turbine technology trends.

The distinction in *qualitative* and *quantitative* scenarios is made, depending on whether the scenarios are built using mostly qualitative or quantitative data. An extreme example of a qualitative scenario uses no trends or estimations but only a storyline for the scenario, whereas extremely quantitative scenarios are made by choosing certain parameters and their possible values. All variations are then examined [94]. Depending on the amount of variables, taking on every variation might mean a great deal of scenarios will have to be developed, for instance only three variables with a variation in a high maximum and a low minimum value will already lead to eight scenarios. Only the most interesting combinations can be chosen, with of course the downside that one has to be able to estimate in advance what these combinations would be.

Implementation paths could be described as a strategic scenario, combining policy changes and actor behaviour with environmental changes. In this study, the choice is made not for a strictly normative scenario to 6000 MW installed capacity but a descriptive scenario for an implementation path towards that target, that is or is not achieved in a scenario. Note that here in this study, the developed model will use environmental scenarios as input. In this research, the term scenario will therefore from here on out always refer to an environmental scenario.

The scenarios used in the research (i.e. the input scenarios for the model) will be descriptive, environmental scenarios that combine qualitative and quantitative data in their development, but will be translated to quantitative data to serve as input for the model.

3.2.3 How to build scenarios

Above categorisations should give an idea of how many different types of scenarios can be made. Scenarios do not have to be strictly fitting to one category (for instance a scenario can combine qualitative and quantitative data). In creating the different types of scenarios, all require an identification of key elements and their relations. The key elements are factors that will have an influence on or be influenced by decision making.

However, 'Scenario planning isn't rocket science', as Schwarz has stated, one of the founders of scenario planning and a rocket scientist himself [263]. Scenario making remains a subjective technique, as there is no fixed method of deciding which factors should be taken into account. As the future cannot be predicted, one cannot predict which factors will have the highest impact on the future and should therefore be considered key elements, let alone predict the value of the key element. Therefore there is no measure of a good scenario in terms of its accuracy in representing the future, only in retrospect can one judge how well the scenarios described the possible changes.

Several ways have been described to make a collection of scenarios. In Schwartz and Wack's intuitive logics, the scenarios are written using different storylines or plots. Such a plot can be 'the winner takes it all', which is used as a plot to make combinations of the key elements to create the scenario. This makes very qualitative scenarios, but many ways of scenario building can in its essence be related back to the work of Schwarz and Wack [216]. Their methodology will therefore be presented.

Schwarz & Wack's steps to create scenarios

The basic steps for scenario making are as follows ([216], [206]):

1. **Determine the key question**
   What question do you want answered. It defines the objective and scope.

2. **Determine the key factors**
   Determine what key factors influence the key question and what major trends can be seen today.

3. **Determine driving forces or mega trends**
   Determine the drivers in the macro-environment that influence the key factors.

4. **Order factors by importance and uncertainty**
   All factors identified in the second step should be ordered on how high their impact could be and how uncertain one is about their occurrence or value.

5. **Design the scenario logics**
   Choose the axis for the scenarios.

6. **Fleshing out the scenarios** A storyline can be used to create the scenarios. One can choose a new storyline or follow one of the 'standard' storylines, such as 'the winner takes it all'. All key factors should be addressed.

7. **Detailed design**
   Detail the scenarios. Work out details and fill in the storyline to a full story.

8. **Implications**
   Evaluate the key question in all scenarios to see robustness or vulnerabilities. Does the story give us a surprising new future?

9. **Selection of leading indicators and signposts**
   Each scenario can be given certain milestones or signpost. If in monitoring the actual developments one sees such signposts actually occurring, it could be a sign that a certain scenario is unfolding.

Schwarz and Wack used intuitive logic to generate scenarios, by using storylines and selecting driving forces. Although this step-method has been designed for the creation of environmental scenarios, one sees these steps coming back in the development of policy and strategic scenarios as well. Driving forces are large external forces within society, such as technological development, changing socio-cultural values or income development. Instead of intuitive logics, one can create a set of scenarios by choosing the two most important and distinct driving forces that influence the key issues. These are then used as two axes to develop four scenarios, one in each quadrant [52]. In the development of the scenarios the key issues are considered in combinations that are internally consistent within the structure offered by the driving forces. For instance, a study of the Ministry of Economic Affairs in the Netherlands used two socio-cultural values as driving forces for their future images of the Netherlands in 2050: the willingness to invest in the long-term or short term thinking versus the amount of international cooperation [177], see figure 3.2.3.

3.3 Methodology of this thesis

3.3.1 Methodology template

Two techniques have been chosen for this study in this chapter. First, agent-based modelling as a simulation modelling technique, as it seems a promising technique to model a complex system of interacting actors that can deal with interacting agents (representing actors) with certain objectives, limited information (data access) and a changing environment influencing the actions of the agents. Different actors should be identified and analysed, to decide how they should be incorporated in the model. Such actors are for instance developers, wind turbine manufacturers and governmental policy makers. As stated in the

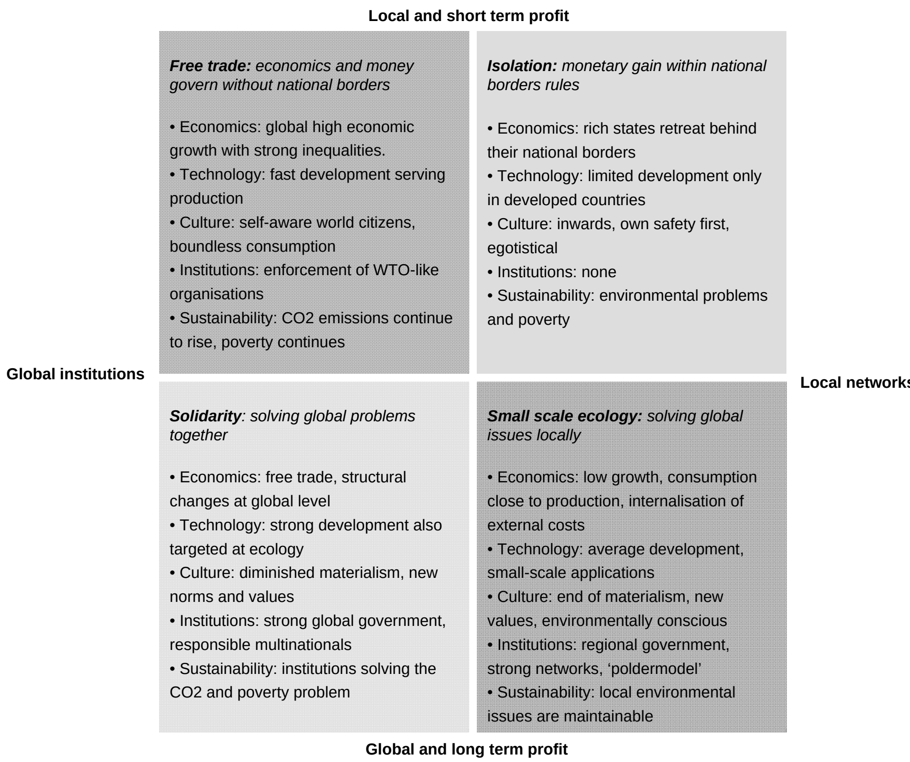


Figure 3.4: Four scenarios of the Netherlands' energy household are created by using two driving forces: a long term versus a short term profit view, and a global or a local cooperation. *Source: [177]*

previous chapter, here the focus will not be on specific companies or other organisations, but on the different *roles* they play.

Second is the technique of scenario planning. Scenario planning will be used to create different environments for the agents. The external factors are a part of the environment of the actors. These external factors are defined as the issues that can influence the actors and the implementation in a positive or negative sense, but over which the actors themselves have no or insignificant control. The achievement of the 6000 MW target for offshore wind power is dependent on a number of such external factors. As these factors and their impacts are subject to change over time and therefore uncertain, the future holds a number of uncertainties for market parties with an interest in wind power, e.g. steel prices and the lobby strength of the shipping authorities.

Both techniques will be combined in one methodology as a step plan to develop an agent-based model. The different stages of development of the model and the steps within each stage are depicted in figure 3.5. The methodology defines a particular set of procedures to tackle the research question. In section 3.1.8, a basic step-plan was given for ABM. Also, methodologies including terminology for agent-oriented system programming were discussed. Parts of the methodology presented here has been borrowed from the agent-oriented methodology Prometheus [192] as described in section 3.1.8. This is combined with procedures of the social sciences and scenario planning. A basic description of the methodology will be presented here, the details and execution of the steps are given in chapters 5, 6 and 7. In short, the steps can be described as follows:

- *Analysis phase*
  - **Actor/factor analysis** Identification of relevant actors, their interests, instruments and power. Identification of the factors using causal diagrams and a field description. Result: Actor Model, focus (the delineation of the socio-technical system under research).
  - **Identification of roles** The actors are divided according to which role they perform in the implementation, separating business units into roles or joining actors that perform the same role. Result: Role Model.
- *Design phase*
  - **Identification of agents** The roles are divided in dynamic and passive roles. The dynamic roles that can change and actively take part in the physical implementation of offshore wind energy in the Netherlands will be modelled as agents, whereas the passive roles will be a part of the environment. Result: Agent Model.
  - **Scenarios** Development of environmental scenarios of the external factors influencing the actions of the agents. Result: Environmental scenario values.

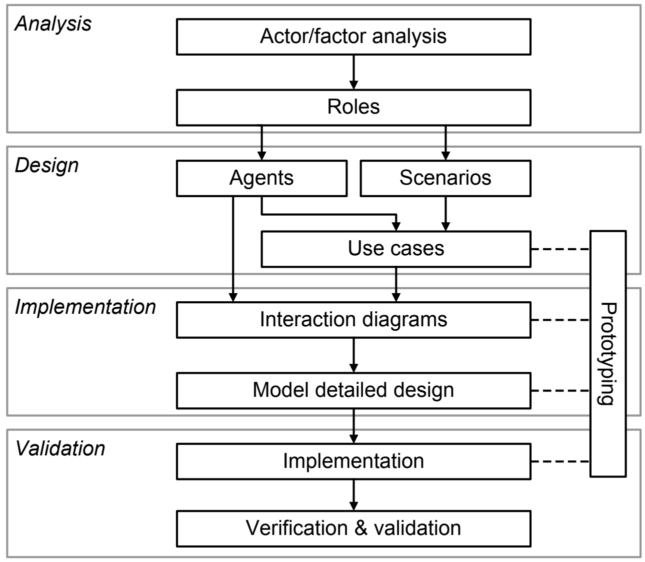


Figure 3.5: The steps of the methodology.

- **Use cases** Description of possible interaction schemes between Agents. Result: Sequence diagrams of important interactions.

- *Implementation phase*
  - **Prototyping** An iterative method will be used to develop the model, as each step gives more information about the desired model and how to implement it. In several steps, prototyping will help to understand the technical possibilities. This step runs parallel with the steps in the design phase. During the identification of the agents, scenarios and use cases prototyping is used to test the technical possibilities in Java and Repast.
  - **Detailed design**: Design of the agents in the AgentModel by defining all their attributes and methods, using the use cases and scenario parameters. Result: ABm design.
  - **Implementation** Writing the program code for the model. Verification of the model by implementing new elements piecewise (unit testing). Result: OweSimModel, the simulation model.
  - **validation** Validation of the model using specific runs with simple initial values, and runs with slight variations in the values of the parameters. Result: Sensitivity analysis.

4

Factor analysis and delineation

Introduction

As explained in the methodology, the analysis phase consists of a factor analysis, an actor analysis and an identification of roles (see figure 3.5). The factors refer to all issues that could affect or could be affected by the (large-scale) implementation of offshore wind energy (OWE). In this chapter, the results of the factor analysis will be presented to come to the delineation of the study. Information for this chapter was collected using literature, interviews and a Group Decision Room (GDR) session. A GDR is an electronic meeting room, where in a session participants can (anonymously) contribute [239]; further explanation follows in section 4.2.3.

In this chapter, first the different aspects of a future implementation of 6000 MW offshore wind in the Netherlands are described. This will lead to a list of relevant topics. Second, the factors named as most important in literature and the GDR session are identified. Third, the delineation is made using the list of relevant topics and the factors named in literature and in the GDR session, and the focus for the development of the model is described.

4.1 Factor analysis

The history and current status of offshore wind energy in the Netherlands is examined to identify relevant factors that could be of importance for the future. After all, the development in the future is dependent on the state-of-the-art and the past as its starting point and its direction of change[1]. To identify the fac-

[1] As North states, path dependency is very real since 'we very seldom change direction completely. The institutions and beliefs of the past have an enormous effect on constraining

tors, two techniques have been used: a variation of a PEST analysis and causal diagrams.

A PEST analysis [233] is commonly used as a market analysis tool to identify developments in the environment of a firm. PEST is an acronym for Political, Economical, Social and Technological analysis, the categories of issues examined in the external environment. It is a tool rather than a scientific method, as it gives a direction for the identification of factors rather than an exhaustive list to test a hypothesis. Other versions exist, such as STEEP, STEEPLED or PESTELI: these versions add Environmental, Legal, Ethical, Industry and Demographic issues to the analysis. The choice of the categories depends on the field analysed. Several templates are available to help identify different types of issues within the main categories. The idea of the use of a PEST analysis here is to identify different factors (with the help of such a template) grouped in categories to help in the analysis of the field as well as the presentation of the results.

Here, a PETES[2] analysis, which adds ecological factors to the list, is used instead of PEST: although environmental issues could have been placed partly under political and partly under social issues according to their effects on policy or public opinion, a more direct approach is preferred.

To aid the identification of the factors, a causal diagram has also been used. In a causal diagram, the causal relations between the factors (e.g. identified in the PETES analysis) are represented by drawing lines between the factors. These causal relations show that a change in one factor causes a change in the other, in a positive or negative sense. To extend the causal diagram, the factors already identified are analysed, by further literature study and interviews, to identify on which other factors they could have an impact or by which they could be influenced. In this manner the causal diagram is used to extend the PETES analysis. The causal diagram is used solely as an aid in the factor analysis (similar to mind mapping), the relations in the causal diagram should not be seen as a detailed description of the relation or a declaration on linearity or non-linearity. Not until the content of the model is discussed in chapters 6 and 7 will quantification be addressed.

In the following sections, the identified factors are presented: the political, environmental, technological, economical and social factors. The content of a category is explained in the first paragraph of each category.

---

the ability to make change in the present and the future.' [173]

[2]Although the name 'STEEP analysis' is more common, here the PETES acronym reflects the sequence of presentation of the issues in this chapter, so chosen because of partly overlapping topics.

4.1.1 Political factors

Political factors include issues such as legislation, regulation, governmental policy, financial incentives, international commitments, lobbying and conflicts. Pressure from interest groups is often named as a political factor, however this is not discussed in this section but in the social analysis in section 4.1.5. Here the past and present is described of government intervention related to offshore wind energy in the Netherlands.

Starting offshore

The oil crisis in 1973 jolted a renewed interest in wind energy in the Netherlands. The Netherlands has a long tradition with wind mills due to the wide use of windmills in earlier centuries to pump water, saw wood or grind flour. Because of this tradition and the good wind resources, wind energy was mentioned by the government as a technology in which the Netherlands could be leading [176]. Unfortunately, the domestic wind energy market did not take off as fast as the Dutch manufacturers had hoped. The low oil prices in the eighties and the stiff competition of Danish manufacturers were hard on the Dutch wind turbine manufacturers, and since the nineties difficulty in on-land siting of wind parks hindered the domestic implementation (see for further details [249], [3], [268], [243], [121]). Because of the siting difficulties, the interest in offshore wind grew.

Already in 1974, the governmental Energy Report[3] stated that in the future wind energy could be placed offshore [176]. The promises of easier siting and stronger wind resources made wind at sea an attractive option, even though it would be more costly. As siting difficulties grew in the 1990s, the Government started making serious plans for electricity generation in the North Sea by wind turbines. After a feasibility study showed the merits of the project, it was decided in 1997 that a demonstration project would be placed near-shore (within the 12 miles zone). This was named the Near Shore Wind Park (NSW), but was later renamed to the Offshore Windpark Egmond aan Zee (OWEZ). Some of the respondents in the consultation procedure questioned the usefulness and necessity of offshore wind. In a following central spatial planning document looking towards 2015 ('Integraal Beheerplan Noordzee 2015', IBN2015) [143], it was stated that the usefulness and necessity were considered proven and need not be addressed in future permit procedures for offshore wind parks.

In 2002, the tender for the demonstration park was awarded to Noordzeewind, a joint venture of Nuon and Shell. Since OWEZ was a demonstration park, a pilot project, it received funding from the state and included the obligation for an extensive Monitoring and Evaluation Programme (OWEZ-MEP). In 2007 this offshore park was commissioned, consisting of 36 Vestas V90 turbines

[3]In fact this was the first Energy Report written by the Dutch Government, as before planning the energy household was left to the SEP (Cooperating Electricity Producers). The oil crisis had made the electricity supply a national concern.

of 3MW rated power each[4]. This is expected to remain the only park within the 12 miles zone, as other parks will be required to be placed further offshore to reduce the visibility from the coast.

For commercial parks, several governmental Departments were still trying to work out the permit procedure and subsidy plan, as it became clear that legislation and regulation of the North Sea had to be adapted for this 'new use', as most laws are only applicable up to and including the territorial waters [207]. Therefore the requests for other parks were withheld: a moratorium was placed for offshore wind parks in the North Sea. There was one exception: the Princess Amalia Wind Park[5] (PAWP), as E-connection had already submitted a permit request for this site before the moratorium was announced. This park of sixty 2 MW turbines has been commissioned in 2008.

The Energy Report of 2002 [178] states large-scale offshore wind energy in the North Sea as desirable and mentioned the target of 6000 MW as 'a possible and necessary step' towards a renewable energy household. Several governmental Departments worked on the 'Nota Ruimte' [142], first intending to point out areas of preference but the eventual document entailed only areas of exclusion. In the IBN2015 [143] these areas were further detailed. The later National Water Plan of 2009 [152] does state two preference areas, one area to the west of IJmuiden at a distance of about 60 km off the coast and one near Belgium, and two search areas in the west and the north nearer to the coast in which the possibilities for locations are to be examined. Developers still select their own site, but the locations in the search areas will meet more scrutiny due to the proximity to the coast and shipping lanes. The preference areas as assigned in the NWP are quite far from the coast and therefore quite costly in exploitation, while the two search areas located at the west and north of the country are closer to shore.

Permit procedures and regulatory uncertainty

In December 2004, the moratorium was lifted; a permit procedure was in place and the MEP (Environmental quality of Electricity Production)[6] subsidy was initiated. The permit procedure refers to the 'Wbr' permit procedure, a permit under the Public Works and Water Management Act (Wet Beheer Rijkswaterstaatswerken). The MEP was a production-based subsidy, offering 9.7 €cts per kWh for offshore generated wind power when it started in 2005 [179].

Several developers placed initiatives for offshore parks by submitting a 'startnotitie' (an initiative), a fairly basic document [208] stating the coordinates and

[4]To illustrate, 1 MW of installed offshore wind power generates the electricity for about 1000 households.

[5]Previously named the Q7 windpark.

[6]It is rather confusing that MEP stands for both a subsidy and the Monitoring and Evaluation Programme of OWEZ: the latter is therefore referred to as the OWEZ-MEP.

basic plans of the site but includes no obligation to proceed. The governing Department (the Department of Economic Affairs) was surprised by the enthusiasm of the developers. The ministry of Finance ordered a stop on the subsidy for fear of the national expenditure on offshore wind: the subsidy for 2005-2006 was set to nil [57]. In August 2006 the MEP was discontinued.

The 'traffic light' policy of the Dutch government has received comment and concern from the market parties; the regulatory uncertainty adds to the risks of developers and their financiers. For the government, the permit procedures in place gave no mode of control, as there were no budget limits set for each year or other financial control mechanisms limiting the number of parks that could receive a permit and subsidy. The submitted initiatives already came to about 10 GW of proposed wind power, taking into account overlap of the sites.

The permit procedure introduced in December 2004, a 'first come first serve' policy, was commented on as being unfair and not transparent, as the criteria for permit approval were unclear and constantly updated as more insight was gained by the permitting office [113]. All the work for the permit procedure, including an Environmental Impact Assessment (EIA), would be for nothing if another developer received the permit before you [165].

In most countries the permit requirements include the obligation for an EIA. However, the developers in the UK receive more security before they have to make the cost of an EIA, in return for certain fees []. In the UK, permit rounds are organised for offshore permitting and developers can express their interest during a pre-qualification phase. A number of projects (up to a pre-determined maximum total amount of installed power) are selected based on the financial standing and offshore and wind turbine expertise of their developers, and the developers of the selected projects are invited to tender for their sites. When entering the tender, developers have to pay a tender fee. When the permission to explore the site has been granted, the tender-winners pay a lease-fee for an Agreement for Lease giving them sole right to develop the site provided that they earn consent (including an EIA) and a full lease within five years.

On the other hand, in the Netherlands an EIA is mainly performed using existing literature, while in the UK 2-year monitoring campaigns had to be performed [50][7]. In Germany, the federal government has assessed many of the risks itself, relieving the task for the developers. Consistent, long term governmental planning can significantly lower the risk for developers, by dealing with regulatory uncertainty in permit approval and cost.

The permit procedures and their runtime have an effect on the application of innovative concepts. For example, the demonstration park OWEZ consists of

[7]This will change if the Strategic Environmental Assessment (SEA) has been performed, relieving some of the tasks of the developers in an EIA.

36 turbines of 3 MW each, while the PAWP has the V80 2 MW Vestas turbines even though its construction started a year later. There was considerable time between licensing and the start of construction, but the turbine choice did not change. To change to the larger turbine the project developer of PAWP would have had to apply for new permits, and under the regulatory uncertainty in that time they might have lost their subsidy and the VAMIL and EIA tax benefits it had received. Flexible regulatory measures would be able to incorporate innovation. Also, PAWP is the first commercial park for the Netherlands. It is a completely privately financed park and financed by support of banks instead of on the balance sheet of large companies such as the OWEZ park is. The banks require proven technology for financing to reduce technical (and therefore financial) risk, and the V80 had a longer track record [247].

Financial support

The permit procedure of December 2004 did not provide the government with any financial control over its expenses, as each permitted park received the MEP subsidy. A new subsidy scheme for Renewables was introduced: the Renewable Energy Incentive Scheme subsidy (SDE)[8] [144]. In November 2009 the rules for offshore wind projects to receive an SDE subsidy were presented as a temporary arrangement [145]. All parks that had received a Wbr permit were allowed to submit to a tender between January 4th and March 1st of 2010. For this tender round, a maximum of 5.312 billion euro has been made available, giving the government a fixed maximum expenditure amount. The tender applicants winning a subsidy were the applicants with the lowest tender amount, until the budget was allocated. To account for the additional costs for parks further off the coast, in the ordering of the tender applications the tendered amount was reduced by a distance correction amount. This distance correction amount is based on the distance of the park to the grid landing point. To illustrate, the maximum distance correction is 0.01625 €per kWh for parks at distances further than 85 km. The actual subsidy amount given is the tender amount minus a correction based on the market electricity price. This price correction is set at a minimum of 0.05115 €per kWh. The resulting subsidy amount is graphically explained in figure 4.1.

In [145] it is stated that the tender scheme for the SDE will presumably give a better selection of the sites. The tender instead of fixed price subsidy addresses the information asymmetry between government and developers in the real costs for offshore wind, as developers now have to determine their own tender amount[9], and they have to present overviews of the expected investment and exploitation costs. The distance correction factor can have an effect in the choice of the sites if the factor is high enough to make sites further off the coast interesting. Since the SDE includes fines if the project is not finished five years after the subsidy assignment, opportunistic behaviour of developers filing false

[8]'Stimuleringsregeling Duurzame Energie'
[9]Up to six digits! [145]

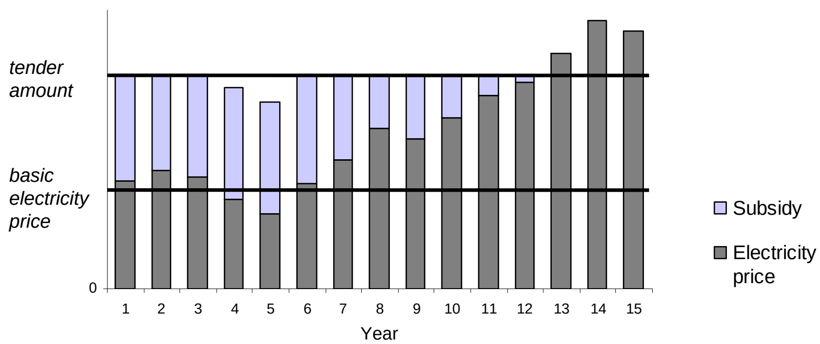


Figure 4.1: Graphical explanation of the SDE subsidy. The x-axis represents the operational year. The subsidy amount given to the operator is the tender amount minus a correction amount. This correction amount is based on the electricity price, but it is set at a minimum: the basic electricity price. One can see that the subsidy received varies over the years: depending on the electricity price, operators can receive in total less or more than their tender amount.

subsidy requests should be minimised.

A German developer has won SDE subsidies for two parks. The remainder of the budget has been allocated for a third park to a second developer and for this park, several innovation clauses has been included in the subsidy [148]. A followup of this single tender round in the Netherlands could be based on the UK tender system, where developers do not have to have the permit (including EIA) to join in the tender. This could reduce developers cost for projects that do not receive a subsidy. However, the rules for the permit procedure would have to be defined and clear to the developers to assess the likeliness of receiving a permit for a location.

Grid arrangements

In the Netherlands, project developers plan and pay for the grid connection of an offshore wind farm. This grid connection consists of the infrastructure from the offshore platform to the high voltage station onshore. In several countries, including the Netherlands, other arrangements have been a point of discussion. The Dutch grid operator TenneT could be made responsible for the roll-out of an offshore grid, to level the playing field between offshore wind and other generation units[10]. This would fit the current responsibilities of TenneT, who maintains and balances the high-voltage grid onshore. Offshore wind farms

[10] Another important advantage is that less cables will need to penetrate through the dunes and dykes at the Dutch coast if an offshore grid is centrally planned [180].

would be able to connect to the offshore connector station, lowering their upfront cost and therefore their financial risk. A previous study [180] has warned that a central layout of an offshore grid with several offshore connection points could lead to under-utilisation of the expensive cables, which would then lead to higher costs instead of economies of scale. Another study [182] has examined the required legislative changes and technical configurations for extending the national grid offshore, as for instance the Electricity Act has to be expanded to be applicable offshore. Assuming an implementation of 5400 MW installed offshore wind capacity between 2012 and 2020, the study estimates the initial investment cost of the offshore extension of the national grid as 3.2 to 4.2 billion €. Under-utilisation of an offshore connector station could be avoided by centrally planning the selection of areas for offshore wind farms.

Other grid arrangements can be seen abroad. For example, in Denmark, the developer is only responsible for the internal grid between the turbines; the grid connection from offshore platform to onshore high-voltage station is the responsibility of the grid owner [2]. The costs are socialised, as consumers pay a transmission tariff to the grid owner to retrieve the costs. In the UK, the Government stated that the offshore transmission should be regulated in the same way as onshore and an offshore transmission owner will be made responsible for the offshore grid connection, reducing the developers' upfront costs [184]. In Germany, the Dutch TSO TenneT is responsible for the construction and operation of several offshore connector stations for wind farms in the German Bight [238]. The consistent long term planning of the German government seems to be productive, as many projects are planned or being installed. If TenneT is made responsible for a Dutch offshore grid, they will benefit from their German experience. Even a Northern-European 'supergrid' has been mentioned (by e.g. EWEA, Airtricity) for the connection of offshore wind farms in the UK, Germany, Denmark, Belgium and the Netherlands.

Main political factors

The way the permit procedures, grid arrangements and financial support are arranged has a large impact on the implementation of offshore wind in the Netherlands. But regulation and legislation also should not change every year, as this adds to the uncertainty for the developers. The main political factors are set in table 4.1.

Table 4.1: Summary of the main political factors identified in the political analysis.

• Permit procedures	• Financial support
• Regulatory uncertainty	• Grid arrangements

4.1.2 Ecological factors

In the political analysis, it was mentioned that an Environmental Impact Assessment (EIA) is part of the permit procedure for offshore wind parks and that certain sites deemed ecologically sensitive have even been completely excluded in the Integral Management Plan North Sea [143] for offshore wind parks. The environmental impact of offshore wind energy has been and still is under investigation, as many uncertainties exist about the impact of an offshore park or parks. Here, the ecological factors are identified, referring to factors concerning habitat loss, mortality, diversity and health of sea life.

Main environmental studies

The environmental impact of offshore wind parks is still uncertain due to a lack of experience. Several studies have now published preliminary results. Most studies follow the BACI method (Before After Control Impact), wherein baseline studies before construction are compared to followup studies performed during and after construction. Three projects are especially of interest: the environmental monitoring programme of OWEZ in the Netherlands [167], the environmental monitoring of Horns Rev and Nysted in Denmark published in [68], and the preliminary results of the FINO-1 test station in Germany published on the FINO website [79].

The demonstration park (OWEZ) tender specification included the obligation of an extensive Monitoring and Evaluation Programme (OWEZ-MEP), in which the impact on several species had to be investigated. Several documents have been published on the website [167] and a short summary of the results can be found in [133]. In Germany, several measurement platforms have been placed in the water. The FINO-1 [11] measurement platform is located close to the Alpha Ventus site [79], the first German offshore wind park commissioned at the end of 2009 [248]. The most extensive monitoring programme published is the programme at Horns Rev and Nysted in Denmark: it includes baseline studies and results during 5 years of operation [68].

Marine mammals

The EU Habitat Directive states which sea mammals are to be researched [130]. In the OWEZ-MEP, seals were added due to pressure from environmental groups. Possible negative effects could be caused by two main issues: sound and the barrier effect.

First, loud noise is propagated through the water during pile-driving. For sea mammals too close to the hammering, the sound waves could damage their

[11] FINO stands for Forschungsplattformen in Nord- und Ostsee.

sensitive ears and thereby damage their navigation capability, which could ultimately lead to death. Mitigating measures can be taken to reduce the noise by creating sound barriers, and to avoid impact and damage. At most sites, pingers have been used during the construction phase, emitting a high-frequency noise to scare the mammals away. At OWEZ, the first results show mammals have been successfully driven off and no rise has been measured in stranded dead sea mammals following construction [167]. In Denmark, the porpoises returned to the site of Horns Rev after pile driving, but at Nysted a decrease in porpoise numbers persisted during the first two years of operation [72]. Seals were only affected during the construction of the Danish parks. Second, the park could have a barrier effect meaning it could form a barrier to seals travelling from rich feeding grounds to breeding waters and back. The results of the Horns Rev park, an important corridor to foraging grounds, showed no barrier effect [83].

The research on sea mammals has sofar produced no worrisome results. Sea mammals are, however, very difficult to monitor and their habitat can change over time (dependent for instance on the availability of food). This makes it hard to ascribe a decrease or increase in numbers to the presence or construction of an offshore wind park(s) [130].

Birds

The EU Bird Directive states which birds should be studied in Environmental Impact Assessments. The birds prevalent in the Dutch part of the North Sea are mostly not on this list but of course still deserve protection [130]. The main issues for birds are possible habitat loss and collision risk, where the latter applies especially to migrating birds.

The results of the collision risk of the Horns Rev and Nysted study are promising. The birds fly around or over the parks and in some cases through the park in a straight line. For possible habitat loss, results show most of the numerous bird species have been displaced by the turbines, temporarily or permanently. However, this effective habitat loss of feeding grounds constitutes only a small portion of the total feeding area and is therefore considered of little biological importance [72]. On the other hand, some bird species are indifferent or even attracted by the parks ([68], [133]). The OWEZ park also sees this attraction of the turbines, as especially sea gulls and cormorants use the structures to rest and sunbathe. The methods used for bird research are bird population counts from boat or air, but these are not perfect. For instance an aerial survey misses birds that mainly fly at bad weather conditions, as surveys are only performed in nice weather [130].

Benthos

Benthos are bottom dwellers at the sea bed. At the sandy bottoms of the North Sea, soft-bottom benthic communities are prevalent. By placing scour protection and foundations in the sea the habitat changes from soft-bottom to hard-bottom locally, and the structures offer grounds for hard-bottom benthic communities such as crabs and anemones. These hard-bottom communities attach themselves to or hide in the hard bottom structures. Biodiversity is therefore generally expected to rise, as hard-bottom benthos densities might rise and they in turn offer more food for other creatures such as fish. In other words, the foundations and the scour protection are expected to form an artificial reef, strengthened by the ban on beam trawling in the offshore park that could increase soft-bottom benthos density[12].

The results at Horns Rev have shown an increase in habitat heterogeneity and a 50 to 150 fold local increase in biomass [68]. At Nysted, the biodiversity was lower, as almost a monoculture of the common mussels was monitored, attributed to the difference in the salinity of the water between Nysted and Horns Rev. At the FINO-1 measurement station it has been noted that up to 5 metres deep, there are mostly mussels present on the structure, but further down at 5-10 metres deep anemones are the dominant species, which attract more fish as they are considered more tasty by the fish [215]. The results of benthos density study at OWEZ showed no measurable effect to the soft-benthos community [133], as the species abundance is similar to the species abundance at control areas, and an increase in the biodiversity on the hard substrata.

Fish

The possible artificial reef effect includes a possible increase of fish population numbers as increased benthos diversity and biomass lead to an increase in available food for fish. Also, the park could act as a sanctuary for fish due to the ban on fishing. It is well known that structures in the sea (e.g. wrecks) attract certain types of fish such as cod, but it is unclear if these new structures will provide a new habitat to live in or if the fish leave after feeding. A reduction in mortality could result in shifts in species composition that could lead to both positive and negative effects due to interactions between species. For instance a reduction in trawling intensity could lead to shifts in benthic composition [63] from soft to hard-bottom benthic communities. If soft benthos availability is reduced, juvenile and/or smaller fish feeding on this resource may experience decreases in growth [127]. Other possible effects on fish are the effect of the electro-magnetic fields around the cables and the effect of noise and increased turbidity of the water, especially during the construction due to the ship movements in the area.

[12] In beam trawling, a large beam is scraped over the seabed to catch benthic fish.

In Horns Rev and Nysted there have been no significant results that show increased numbers of fish around the foundations. Only sand eels seemed to be attracted to the park as their numbers inside the park have risen, but longer monitoring is required for definite results. At the FINO-1 measurement station, it has been noted that several species are very abundant in deeper waters near the foundation. It is unclear however whether the fish just come to feed or they stay in the park [215]. For the OWEZ site the fish do not seem affected by the park, although some fish species such as cod seem to find shelter in the park.

Main ecological factors

From these main studies, the results are hopeful in the sense that so far no definite negative environmental impact of offshore wind farms has been reported. All the environmental studies do warn for extrapolating the results to other sites, as different sites would give very different results because of the variation in species, seabed, currents or water depth. Even though initial results are hopeful, the great concern is the cumulative effect of several parks. For instance bird effects might be relatively small for one park, but migrating birds might not have enough energy to go around several parks. It is unclear whether the parks should be spread out to avoid such a great barrier effect. Some environmentalists actually advocate one large area for offshore wind parks, where the layout could be designed in an integral, optimal manner to minimise environmental impact [131].

The main issues remaining for the environmental impact of offshore wind therefore concern the cumulative effects of several parks and the difficulty of extrapolating the results to other sites, as well as the development of mitigating measures. Main factors of concern are the possible (temporary) habitat loss especially for certain birds and mammals. The possibility of the development of possible artificial reef over time or a fish sanctuary are also points of interest in ecological studies. The main ecological factors are summarised in table 4.2.

Table 4.2: Summary of the main ecological factors identified in the ecological analysis

• Cumulative effects	• Extrapolation of results to other sites
• Mitigating effects	• (Temporary) habitat loss
• Artificial reef effects	Sanctuary effect

4.1.3 Technological factors

In general, technological factors are issues concerning competing or dependent technologies, research funding, the maturity of the technology, the maturity and capacity of manufacturing, information sharing, technology legislation, innovation potential, technology access, intellectual property issues and consumer buying mechanisms. The relevant technological factors for offshore wind energy are identified as follows.

Offshore wind turbine design

Offshore wind started with placing onshore turbines offshore. The famous example is the Horns Rev wind park, the first offshore wind park in North Sea conditions, where this led to the major overhaul requiring all nacelles to be taken onshore [252]. The turbines are now more adapted to the marine environment. For instance, to keep the salt air out of the nacelle, the wind turbine air conditioning keeps the internal pressure slightly higher than outside. The offshore turbine design is more and more headed towards a true offshore turbine and greater changes might come in the future.

Because of the cost of the foundation, the focus lies on larger turbines than is usual onshore, and wind turbines have grown considerably the last decades. The turbines most installed in offshore wind parks by the beginning of 2010 are the Vestas V80 and V90 of 2 and 3 MW respectively, and the Siemens 93 and 107 of 2.3 and 3.6 MW respectively. Each of the four types have over one hundred units installed. Several turbines of around 5 MW installed power are on the market and are of German make: Multibrid, Enercon and REpower. The Enercon E126 is a 7 MW direct-drive wind turbine, but has not been applied offshore[13]. The Multibrid M5000 and REpower 5M are used in the first German offshore wind park Alpha Ventus, a demonstration park testing these 5 MW turbines to a marine environment. Other 5 MW turbines are the Bard VM 5MW machine[14] and the XEMC-Darwind direct drive wind turbine. Market leaders Vestas and Siemens have also increased their turbines' rated power capacity. Siemens ([7], [8]) started operating their 6 MW SWT 6.0-120 in June 2011 and has sold 300 units of their SWT6.0-154 in July 2012. Vestas is planning an 8 MW rated power prototype in 2014 [9]. Designs of 10 MW and more are being examined, for instance in the Icorass project and in the Upwind project. The Icorass project entailed an initial concept feasibility study examining the upscaling effects to a two-bladed downwind 10 MW turbine [31]. In the Upwind project changes for wind turbines in the order of 10-20 MW are considered. An aspect under investigation is the use of smart blades: as the blades grow larger, one has the possibility to place control devices in the blades themselves to reduce the loads [244].

If upscaling continues, very soon the blades might be too large for transport onshore[15]. It might become necessary to place the factories near the coast for transport over water or design blades of more than one piece and assemble them

[13] The E126 was initially rated at 6 MW at introduction in 2007, but since 2009 is rated at 7 MW. Enercon published that the E126 can even run safely at 7.5 MW rated power [66]

[14] BARD announced it is scaling up this turbine to 6.5 MW by summer 2010.

[15] Already accounting for this, the Enercon E126 has blades in two components that can be transported separately [66].

on the harbour site. Completely other concepts could arise, as for instance the AerogeneratorX 10 MW vertical axis turbine [1]. The limits to size will be due to a variety of reasons: manufacturing capability, transport, onshore assembly, ship size and the price of the wind turbine and the foundation [247].

Offshore planning and installation

Placing the wind turbines in an offshore environment not just impacts the wind turbine design, but also the planning, installation and operation of a wind park. For planning, one has to take into account the shape of the sea bed, sand waves and currents of the site. Placing them near shore in shallow waters is not necessarily better than further offshore, as breaking waves cause considerable loads on the structures.

Onshore one installs the turbine under fixed world conditions; the turbine parts and the crane hoisting the parts are on the same plane. Offshore, installation has to be done from a vessel in a moving sea. There are for instance jack-up vessels, where a vessel lowers legs onto the ground to lift itself up so it is less susceptible to the waves. Getting the legs in and out of the water is however time-consuming and such special purpose vessels represent a considerable investment.

Offshore installation is more expensive than onshore installation, due to the cost of required resources such as jack-up vessels or Heavy Lifting Vessels as explained above, and also due to the possible delays due to weather. This means that everything that can be assembled onshore is a cost reduction. Extensive new concepts are examined of installing a completely pre-assembled wind turbine (and a foundation) in one lift. For example for the Beatrice site in Scotland the four-legged truss foundation was placed on the seabed and the complete wind turbine with nacelle, hub and blades was carried from the harbour to the foundation [22].

To achieve the implementation of 6000 MW by 2020, the availability of required resources such as special-purpose vessels might fall short. For instance, apart from the considerable investment it also takes several years to build an installation vessel. The implementation speed could be hampered by the number of available resources e.g. installation vessels and offshore wind turbines. Also resources such as foundations and turbines need to be available.

Operation and maintenance

A wind turbine is considered available when it is technically capable to generate electricity from the wind, independent on the actual wind conditions. Theoretical availability refers to the characteristics of the turbine, its reliability and ease to repair and maintain, while true availability also takes into account accessibility of the site and the adopted maintenance strategy [34]. But the accessibility of an offshore wind park is lower than a park on land. A vessel or helicopter may not be able to travel, let alone transport personnel to a turbine, in certain weather conditions such as high waves and strong winds. The accessibility of an offshore site may therefore drastically reduce the true availability of a site. It is therefore important to increase the reliability of the turbine and its ease to repair and maintain, as well as devise better access methods.

Future innovations could increase the availability of wind turbines. The changes to offshore wind turbine design have already been discussed, as for instance different drive train options are examined. Reliability of the wind turbine might be increased by eliminating the fault-sensitive gearbox (the direct-drive concept), as this is one of the components causing the most downtime [72]. But also in operation and maintenance possible improvements are examined, as for instance remote monitoring and remote reset can increase the availability. Adding an internal crane in the nacelle can make maintenance easier, by allowing larger parts to be replaced without having to mobilise special crane vessels. New access methods promise to increase the accessibility of a park, such as catamaran vessels or the Ampelmann system that can be placed on an existing vessel and can hydraulically counteract the motions of the waves [5].

Grid integration

Often mentioned as of great concern is the grid integration of large-scale offshore wind power (e.g. [81], [190]). Because wind power is variable[16], balancing the power system could become harder and the question arises if 6000 MW of offshore wind power can be accommodated by the current power system. In 2020, wind power could supply about 18-24 % [17] of the total electricity demand in the Netherlands. In [72] is stated that if the penetration level of wind power exceeds about 20 % the current power system might not be adequate and might require changes and a different method of operation. Such changes include reinforcements of the grid and a more flexible grid. Flexibility of the grid can be achieved by e.g. greater interconnection capacity for trade and energy storage.

Several studies have been performed to investigate grid integration in the Netherlands and they show that although at connection stations capacity might be limited [182] and stronger interconnection is required for better trade and balancing, no energy storage is required to integrate up to 10 GW of wind power in the Dutch grid [107]. The results of a PhD research[18] [241] showed that

[16]Wind power output is sometimes referred to as being intermittent: however intermittency means alternately stopping and starting. Wind power output change is more gradual, and therefore one should speak of a variable power output.

[17]If we assume 2000 MW installed wind power onshore with a capacity factor 30% and 6000 MW offshore with capacity factor 45%, wind generated electricity supplies about 18 to 25 % of the total electricity demand in 2020. Electricity demand in 2020 is taken varying between 123 TWh (constant growth, remaining at 2008 level) and 155 TWh (linear demand growth)

[18]This PhD research is also part of the PhD@Sea project.

8000 MW (of which 6000 MW offshore) can be fed into the grid without the need for power system changes. A quick-scan [240] showed no otherwise wasted wind energy will be saved by any of the five researched energy storage options[19] and the storage facility will be mainly used to replace gas peak power by cheap coal based power, increasing the overall CO_2 emissions by about 2 Mtonnes per year. For the 6000 MW target, the grid integration is therefore considered not a relevant technical factor[20].

Technical requirements wind turbines

Generators connecting to the grid must comply to certain technical requirements, often referred to as 'grid codes' [72]. The three main issues for grid codes relate to voltage and reactive power control, frequency control and its related power control, and the fault ride-through capabilities [54][21]. Denmark and Germany both have grid codes for wind parks [4], for instance wind parks are required to be able to limit the power output at a certain ramp rate, and wind parks might be required to postpone cut-off of wind turbines in a park during a storm to attain a more gradual reduction of power. They are required to supply a certain amount of reactive power when requested. Requirements are set for the ranges when a wind park has to have sustained operation during system disturbances.

In the Netherlands, there are no specific grid codes for wind parks. Variable sources-power generators such as wind are not required to supply primary reserves, reserve power or reactive power. While generation units are required to handle voltage dips, in practice the developer and grid operator make an agreement on what is technically possible and required [123].

Innovation

In [129], different possible technology developments are identified divided in three categories: incremental change, new main components and new concepts. Incremental change includes innovation related to efficiency of design, design conditions identification, control, materials and resource prediction. New main components include new concepts for blades, materials, structural design, conversion, grid integration and the foundation. New concepts apply to innovation to the complete design, e.g. two or three bladed turbines, downwind or upwind turbines or offshore Darrieus wind turbines.

[19] These energy storage options are Compressed Air Energy Storage (CAES), the OPAC in Zuid-Limburg, the energy island, flexible CHP and a second NorNed cable.

[20] It is a relevant political factor, as the capacity of some high voltage stations needs to be upgraded.

[21] DeAlegria et al explain the different manners at which wind power could meet such requirements in a clear manner.

Such technological innovation to the turbine, grid connection, installation, operation and maintenance could reduce costs and increase the availability of the offshore park. Although innovations cannot be predicted, trendlines can be made for incremental changes such as upscaling; but such graphing will not take into account the effect of new components and new concepts.

Main technological factors

The main technological factors as discussed in this section are summarised in table 4.3.

Table 4.3: Summary of the main technological factors as identified in the technological analysis

• Wind turbine size	• Wind turbine innovation
• Availability of resources	• New installation methods
• Wind turbine true availability	• Operation and maintenance strategies
• New concepts	• Grid codes for wind turbines
• New materials	

4.1.4 Economic factors

In general, economic factors are issues concerning, on the macro level, the (national and international) economic situation, interest rates, tariffs, inflation, consumer drivers, markets and production levels. Industry specific factors include the costs and comparative electricity generation price of offshore wind versus fossil fuels.

The costs of offshore wind

While an onshore wind park is one of the cheapest forms of renewable energy generation (e.g. [251]), an offshore wind park is considerably more expensive. This is due to the higher cost of installation and operation and maintenance costs due to the offshore siting, the additional costs of an offshore grid and adaptation of the turbine.

As offshore wind matures, the hope is that cost reductions will make it cost competitive with fossil fuel electricity generation. Junginger estimated the cost development using learning curve theory [119]. Learning curves represent expected cost reductions due to learning: when experience is gained, routines and optimisations can lower the costs. However, current costs are higher than estimated by Junginger, partly due to the high material costs. The high steel price around 2005-2010 have made wind turbine prices rise instead of fall. On the other hand, the recent high oil prices have made the relative price to other generation units more competitive. Estimating a future price for offshore wind is certainly influenced by learning, but other aspects influence the price as well.

The internalisation of external costs of electricity generation

Financial arrangements might improve the price of offshore wind relative to fossil fuel generation, such as the internalisation of external costs. ExternE, a study by the European Commission into external costs, defines and describes external cost as [44]:

> An external cost, also known as an externality, arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group. [...] the environmental costs are external because, although they are real costs to [other] members of society, the owner of the power station is not taking them into account when making decisions.

The market price of electricity generation does not represent its complete costs to society if its external costs, the emissions that damage the environment and human health, are not taken into account. The ExternE study [44] examined the impacts from the production and consumption of energy-related activities and it showed that wind energy has the lowest impact on environment and health [22] measured by the amount of air pollution and greenhouse gases emissions. It should be noted that although for fossil fuels, all impacts in the 'fuel cycle' (from extraction to consumption) were identified and quantified, for wind the processes of the entire life cycle were taken into account, so the scope was broader for wind energy [42]. For the Netherlands, the external costs of coal and gas are calculated as 3-4 €cts/kWh and 1-2 €cts/kWh respectively, while the external costs of wind can be estimated as 0.05-0.1 €cts/kWh [23]. Economic activities can take such external costs into account, in other words such external costs can be 'internalised'. An example is eco-taxes: polluters are taxed according to the damage of their economic activity, making environmental cost a part of the decision making. In the case of the CO_2 emission system polluters pay for the right to pollute. One of the main reasons for the set-up of the CO_2 emission system has been to take into account the external cost.

Market design

For the offshore wind farm operator, the income generated by the farm is the electricity price received from the market and possible governmental financial support. Park operators usually close Power Purchase Agreements (PPA's) with electricity utilities for their generated kWh. In the Netherlands, wind

[22] The compared technologies were wind energy, nuclear energy, biomass technologies, natural gas technologies and coal technologies.

[23] The external costs of wind were not calculated for the Netherlands, but the Danish (0.1 €cts/kWh)and German (0.05€cts/kWh) calculation are considered comparable.

power plants are considered conventional power plants in the balancing of the grid. An imbalance price has to be paid for deviation from forecasted power supply. In this market design, the price received for wind depends therefore on how well the operator can predict the output. Because wind is a variable source and not fully predictable, a higher or lower power output than predicted is penalised with a balancing cost. In the PPA's, these balancing costs are taken into account in the price operators receive. Reliable wind predictions are therefore important for a good market price of wind energy for an operator. Better forecasts would improve power prediction and would therefore lower balancing costs arising from the difference between predicted and realised power output. Other measures such as shorter gate closure times would also lower balancing costs, as predictions become more accurate when the prediction time is shorter: day ahead predictions can show great variations, while hour-ahead predictions are usually well-fitted to the actual occurring generated power.

Other market designs are in place. For instance in Germany, wind energy is prioritised: all wind generated electricity is fed into the grid, and the balancing of supply and demand is done with the other generation units[24]. The wind energy generator operators receive a Feed-in Tariff for their generated kWhs. In the Netherlands, all generated electricity is bid into the market for a price the generator wishes to receive. Wind energy has a relatively low operational cost, as there is no fuel cost, and the generated wind power will be bid into the market at low prices. Because of this low bidding in the market, wind energy lowers the overall electricity price in such a liberalised power market [155].

Financing and risks

Although offshore wind power has a relatively low operational cost, the upfront or investment costs are high. The large upfront cost (and long lead times) creates financial risk for the developer. As mentioned in section 4.1.3, the layout of an offshore grid is under discussion. Such an offshore grid could lower financial risk by lowering the investment cost, as the offshore grid connection represents about 15% of the total investment costs [157]. Other risks are the technical risk and the regulatory risk, the latter because of the dependence on permits and financial support for the achievement of the project. These risks can make financing a project more difficult.

For onshore, project finance of wind projects is getting easier, as more banks are willing to give out loans as the risks have been reduced and track records are getting longer [72]. For offshore, most realised projects have been financed by the company's (and investors') assets. For a general project, usually project financing is used, meaning a loan from a bank or banks. Often a company (or

[24]In the new Renewable Energy Directive, priority and guaranteed access are mentioned as important for integrating Renewables into the market, but it does not state any obligation for the member states [45].

investor) would make a portfolio of projects and sign a loan at a bank for this portfolio, thereby spreading the risk over several projects. Several offshore wind projects have been financed by project finance. The second Dutch offshore wind park has a special financing structure: non-recourse project finance for the entire project. This means that the collateral for the loan is only based on the project, not the other assets of the borrower [187]. Although previous projects, such as North Hoyle, have used non-recourse project finance, in their case this was only for the loan post-construction: then the collateral has already been built and the banks bear no construction risk.

The technical risk due to the lack of a strong experience raises the investment risk. Even though the cost per MWh is expected to be lower for parks using large wind turbines, the money lenders and insurance companies may require more proven technology instead of the newest, largest turbines for good interest rates and set-up fees. This could inhibit the progress and cost reductions innovation can bring [242].

Main economic factors

Above we have described market options of internalisation of external costs, priority access, and electricity market design. Changes to these will have an impact on the relative cost and balancing cost of wind power. The costs of offshore wind parks are internally influenced by the measure of innovation and externally influenced by material costs and demand. The main economic factors are summarised in table 4.4.

Table 4.4: Summary of the main economic factors as identified in the economic analysis

• Internalisation of external costs	• Priority access
• Electricity market design	• Raw material cost
• Proven technology vs. innovation	• Investment risk
• Offshore wind turbine supply and demand	• Balancing costs
• Onshore wind turbine supply and demand	• Relative costs

4.1.5 Social factors

Social factors include issues such as people's attitudes and opinions, the image of the technology and lifestyle trends. Here we discuss the social factors specifically applying to offshore wind in the Netherlands and therefore look at the attitudes and opinions of other users of the North Sea and the Dutch coast. The concerns of these interests groups are discussed here, as they form the social environment for offshore wind parks.

Other users

Many activities take place on the North Sea, such as fishing, sand collecting and shipping. Areas have been assigned to such users that are therefore excluded for offshore wind park sites [152]. It may be possible that such an assignment of an area could change, for instance OWEZ is constructed on an old military practice field. The recent National Water Plan (NWP) however does not mention possible future assignment changes [152].

With Rotterdam Harbour as Europe's largest cargo port, one can imagine that the shipping interests are considerable in the Netherlands. The shipping lanes for large ships run all along the Dutch coast. For shipping safety, it is important that offshore parks are located at a safe distance from the shipping lanes, e.g. a drifting ship could drift for several miles. This raises the question what a safe distance is. An earlier investigation was made using the SAMSON model, a model that simulates ship movements in the North Sea. It concluded that offshore wind parks near shipping lanes would only have an insignificant disruptive effect, but shipping authorities were still concerned for a safe distance especially concerning special manoeuvres. The shipping authorities raised the question again during the consultation processes of several permit requests [113]. This led to the installation of a special committee, whose recommendation was that no offshore wind parks should be located near shipping lanes and anchor sites. The committee only included stakeholders from the shipping sector and two governmental employees, leading to comments of developers on the subjectiveness of these results.

Offshore wind farms can lead to a loss of fishing grounds, as fishing boats are prohibited to enter the park sites in the Netherlands. Fines have already been given to fishermen going into the park area regardless. The fishing activities can damage the underwater cables between the turbines, which would lead to a costly repair operation. Also, the nets sometimes fish out equipment used for the environmental monitoring, which could cause a lack of data for a period until it can be put back in place[25]. Beam trawlers have also been spotted at the sites and their method of fishing, stirring up the bottom to catch bottom-dwelling fish, disrupts a possible artificial reef effect. Combined use of the area has been discussed, e.g. mussel farming is possible by placing nets between the turbines, but the effects of the nets on the turbine support structures are not fully evaluated yet.

Turbines reflect radar signals, giving a 'ghost image' of itself on ships' radar image, see figure 4.2. This is of concern for ships who need to navigate at a safe passing distance to offshore parks using their radar. The issue of radar disturbance has been rated on a low priority in the Netherlands [112]. In the UK the ghost image of existing parks have been shown to lead to quite a disturbed image on the radar and radar personnel will need extra training to be able to

[25]One needs a minimum of measurement 'Tpods' in the water for a reasonable accuracy.

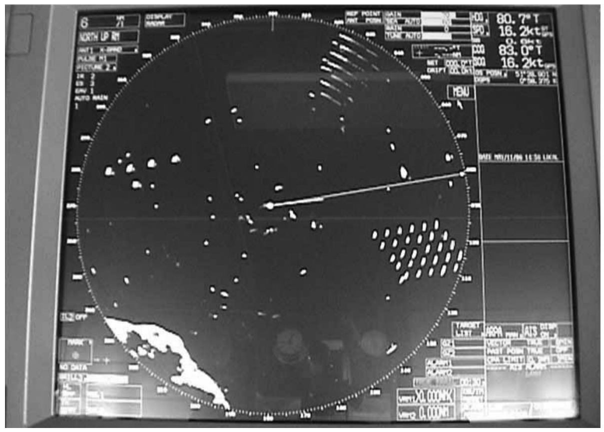


Figure 4.2: Example of a radar disturbance by an offshore wind farm on 'Dredger OSTSEE using 3cm radar (port scanner). The reflections of the wind farm are caused by the approaching vessel on the port bow. These reflections were noted to be rotating around this vessel.' [137].

read such an image accurately. The cumulative effects of several parks might lead to more difficulty [137].

Public opinion

In good weather conditions, parks nearer to the coast such as OWEZ can be seen from the shore. The OWEZ-MEP therefore included a study on the public opinion on the wind park, spanning over several years to include the time before, during and after construction [90]. Four groups were questioned; local inhabitants, local business owners, Dutch tourists and German tourists. In general, there was a rise in the percentage of people who thought that the sea was a good location for wind parks. Before construction 54-66 % of the groups said it was a good location, rising to 74-89 % in 2008 after the construction. Especially the German tourists were more apprehensive at first with the lowest percentage of 54%, but showed the greatest support for offshore wind after construction at 89%.

In Denmark, the studies showed that people would be willing to pay a higher electricity bill to have the offshore parks further off the coast, especially the people near the Nysted park [68]. The Nysted park lies closer to the coast than Horns Rev and during its first year the night lights on top of the turbines were not synchronised, leading to the nickname 'the discotheque'. This could be the reason why especially the people close to the Nysted park would be willing to pay more for their electricity bill for a park further offshore. In general, the studies showed a positive public opinion of the two parks.

Main social factors

There are many other activities at the North Sea and in assigning locations for offshore wind parks governmental decision makers have to take into account the interests of all users, e.g. the dredgers, fishermen, shipping and sand collectors. Especially the safety of shipping lanes is an issue in locating parks, and the disturbance of the radar of a great number of parks may become an issue. Possible combined use might give new possibilities. For the people at the coast, good information ahead of construction and the distance to the coast should ensure high social support. For the consumers, the social cost (affordability of electricity, cost of subsidies and other financial measures) are of importance. The main social factors are summarised in table 4.5.

Table 4.5: Summary stating the main factors identified in the social analysis.

• Available areas	• Shipping safety	• Radar disturbance
• Distance to coast	• Social cost	• Combined use

4.2 Delineation of research

4.2.1 Making a selection of the factors

Different aspects of the socio-technical system to be (partly) captured in the model have been described, and in this section the delineation will be made. The model should include the most relevant factors: the factors considered to have the highest impact on the implementation of offshore wind energy in the Netherlands. More specifically, the factors to be selected should be relevant for the target of 6000 MW installed offshore wind power in 2020, defining the scale and time horizon. To help decide which factors are most relevant for this large-scale implementation, the main factors identified in the previous section are examined and compared to other studies and in a brainstorm meeting with experts in a GDR the factors were ranked according to impact.

4.2.2 Previous research

Several studies have made an identification of the important factors with high impact to offshore wind in general. In these studies, the topics that are often described as topics requiring attention are the grid integration, regulatory issues and the environmental impact. A few examples will be given.

The Copenhagen Strategy [229] is a followup meeting to the Egmond EU Policy Workshop [183] intended to focus on the solutions, approaches and structural cooperation between parties based on identified obstacles for offshore wind energy in the EU. The market, grid integration and environmental impact are named as issues for which there is a need for new solutions and more cooperation [190]. For the market, several regulatory issues are identified as of importance , e.g. a stable regulatory framework and efficient decision making procedures; and the achievement of a larger market volume and larger turbines for cost reductions (for instance by demonstration projects).

In the COD study [81], the aim was to speed up implementation of offshore wind energy by identifying (and possibly removing) the non-technical barriers. Information was gathered and analysed on grid integration, planning and consent procedures, and environmental impact. It concluded that for the grid integration of large-scale offshore wind, the main issues were financial issues and timing, not technical issues. This is because the required grid connections and grid reinforcements mainly concern technically feasible measures. For the environmental impact, there is a knowledge gap that needs to be addressed. Evaluation standards need to be set such as duration or frequency of the investigations, and the research should deliver data that can be used in higher scale research for cumulative effects such as an SEA (Strategic Environmental Assessment). Assessment tools for cumulative effects need further development. In planning and consent procedures, there was great diversity recorded between countries but there is not enough experience with offshore parks to be able to state ‘best practices’ [82]. Harmonisation is not required as the diversity could be seen as ‘risk spreading’, but attention has to be given to making procedures more precise and transparent, to pre-selection of sites using an SEA, and to a transnational development.

The European Wind Energy Association (EWEA) is an association for market parties and research institutes in the wind energy industry. In EWEA’s 2009 offshore report ‘Oceans of opportunity’ [78], the main challenges and topics of interest for offshore wind were identified as: wind measurements and wind characteristics, innovation in wind turbines, manufacturing processes and capacities, spatial planning, and availability of personnel.

In a report by 3E and EWEA [220], legal and regulatory issues were investigated for offshore wind and the best practices were named in procedures, economic costs and economic incentives. These best practices are given in table 4.6. The best practices are policy options for permit procedures, financial support and risk-reduction. In a one-stop-shop procedure, the developer only has to deal with one governmental authority in the consent procedure, to shorten runtime and facilitate the procedure for the developers. Certain anti-speculation clauses in a permit can ensure that a developer cannot hold a claim on a location indefinitely without installing a wind farm, such as penalties or a loss of the concession. Securing pioneering risks, by for instance granting premiums or Feed-in Tariffs per kWh, concern the financial support. Because of the relatively long lead times, regulation for consent procedures should allow for innovation without loss of the consent. Transparency in the burden on the project developer concerns a clear description of option and lease fees and other costs for the permit request. Sharing the burden of the grid by sharing with or placing responsibility at the onshore TSO will reduce the financial risk for the investors and policy initiatives for this concern the arrangements for the offshore grid.

Table 4.6: Best practices for legal and regulatory issues.

• One stop shop procedure	• Anti-speculation clauses
• Securing pioneering risks	• Allowances for innovation
• Transparency in financial burden for project developer	• Burden sharing for connection to grid
• Risk hedging schemes	• Monitoring requirements
• Decommissioning and rehabilitation guarantees	• Enhanced communication and public involvement

4.2.3 Ranking of factors in the Group Decision Room

A GDR is an electronic meeting room, where participants share their vision on the chosen topic in a structured discussion led by an objective facilitator. The discussion usually starts by identifying the factors influencing the topic, followed by a discussion of the results, a ranking of the factors and further discussion of the results. In the identification, the participants type their contributions on a workstation connected to a central system that collects the data [239]. In this manner, the participants can work in parallel and their contributions are anonymous. The contributions are discussed, to see if they are clear to everyone and to remove duplicity (replace similar factors with one description). Because the contributions are made anonymously, the impact of a hierarchy (e.g. company hierarchy) in the meeting or presumptions of bias can be reduced. The revised list is then given for ranking. The participants give their view on how important certain factors are, and what their impact is on the overall topic of the GDR. This can be done in different ways, e.g. all factors are given a number on a scale or the participants make a top five. The results of the ranking are subsequently discussed in the group to create consensus. This consensus building for the results derived in the group effort can help create a sense of ownership of the results.

In July 2005, a GDR was organised for this research and 18 people from different companies and interest groups joined in in the discussion about the main bottlenecks and opportunities for OWE in the Netherlands [138]. In the GDR, the participants were first asked for factors relating to large-scale implementation of offshore wind in the Netherlands. The factors were discussed to clarify possibly vague terms and to remove duplicity. The list of 200 initially identified factors was reduced to 40 by voting. The participants were asked to grade the 40 factors from ‘not very important (1) to ‘very important’ (5) and ‘uncertain’ (1) to ‘certain’ (5). The results were discussed and the participants then gave their opinion on the time scale for each factor when it could play a role: short term, medium term or long term.

Fourty distinct bottlenecks and opportunities were identified and graded for importance and uncertainty. The results of the GDR meeting are given in tables 4.7 and 4.8. It should be noted that in the year of the GDR, the moratorium had been lifted and subsequently the MEP had been set to zero, so it is understandable that the governmental policy received high attention.

Table 4.7: GDR results: the barriers and opportunities of highest impact and *high certainty.*

Barrier	• Inconsistent government policy. • Unequal playing field compared to other generation sources. • Lack of a governmental long term vision.
Opportunity	• High fossil fuel prices. • Stronger environmental effects of fossil fuel emissions.

Table 4.8: GDR results: the barriers and opportunities of highest impact and *high uncertainty.*

Barrier	• No availability of wind turbines. • Large technical failures.
Opportunity	• Consistent governmental policy. • No hidden subsidies for high emission generation sources. • Large nuclear disaster.

The factors identified were graded along their certainty and impact for the making of the implementation paths. Very certain factors should be incorporated in all paths, whereas uncertain factors, especially those with a high impact, can be used as differentiating factors between the paths. As a final question, the participants were asked which *target variables* could denote the value of a scenario. These target variables are variables whose value would be indicators of how desirable a certain scenario would be. The identified target variables are given in table 4.9.

A more detailed report on the GDR results is given in [138].

4.2.4 Chosen focus for the research

The socio-technical system modelled in the agent-based model to be developed will be delineated, based on the choice of the focus on certain factors. For the choice of this focus, first the importance of the factors as mentioned in the factor analysis, previous research and GDR is considered. Second, a certain width in

Table 4.9: The target variables representing indicators of the desirability of a scenario, as identified in the GDR.

Political	Speed of implementation in MW per year
	Required change of policy
	Required subsidy per kWh
	Total required expenditure
	Responsibilities government
	Contribution to GNP
	Share of Dutch industry in OWE
Ecological	Environmental impact on flora and fauna
	Reduction of CO_2 emission
Technological	Required innovation
	Resource availability of offshore wind turbines
	Effect of OWE on security of supply
	Grid connection possibilities at sea
Economical	Electricity price per kWh
	Internalising external costs
	Division wind parks operational and investment costs
	Total electricity production in TWh in 2020/ per year
	Security of supply
	Share OWE in electricity supply
	Investment risk
	Created employment in man year, directly and indirectly
Social-Environmental	Social support
	Occupied surface OWE
	Exclusion by and cooperation with other users

topics is preferred to test the agent-based model's applicability to the incorporation of different viewpoints in a dynamic socio-technical system, although the selection does not necessarily have to reflect one political factor, one ecological factor, etc.

A topic often mentioned as of high impact on the development of OWE in the Netherlands is governmental policy and regulatory uncertainty. In the GDR, this factor was identified as the factor with the highest impact in both possible barriers and catalysts for the implementation. The political analysis and the previous research have shown that permit procedures and financial support schemes and their stability are especially important. The way permit procedures are executed is a particular generator of regulatory uncertainty, and for instance Shaw [220] showed which best practices can be identified. The combination of permit procedures and modes of financial support cover a large part of the regulatory uncertainty, and incorporating different regulation for these topics should have a visible effect on the chosen indicators implementation speed, relative costs and total required subsidy. It has been chosen to include permit procedures and financial support in the focus of the model to compare different policies in different simulations and assess their impact.

Also related to governmental policy, but with a strong technical content is the layout of an offshore grid. Whether or not an offshore grid will be centrally realised is uncertain and the layout of an offshore grid by the grid operator will have a significant effect on the costs for the developers. As presented in 4.2.2, grid integration is considered of major importance in several studies and might therefore be expected to be included in the focus of this study. However, as stated in the technological analysis, previous studies show that the integration of up to 6000 MW will not present major technical difficulties or uncertainties. The grid integration is therefore not included in the focus. The possible central layout of an offshore grid is included in the focus.

The technological analysis discussed the importance of innovation, and EWEA identifies the innovation of wind turbines as a main challenge for the future of offshore wind. It is of course not possible to predict which innovations or new concepts will arise and be successful, but of importance here is the impact that these innovations can have on the implementation. Here, innovation of the wind turbine will be included in the focus, represented as rated power per turbine and unit cost per rated power, as these will have an impact on the overall cost and required subsidy to accomplish 6000 MW offshore wind power.

In the technological analysis the importance of the availability of resources was discussed. This resource availability has a large impact on the realisation of offshore wind in a specific time period as it determines the maximum implementation speed. Several studies, e.g. [78], [190], [72], and the GDR mention the importance of the resource availability of wind turbines in particular. Here the resource availability of wind turbines will be included in the focus for the model. The resource availability of wind turbines can be very directly linked to the actions of actors, as it is dependent on the strategies of wind turbine manufacturers based on their estimation of the onshore and offshore wind turbine demand.

Not directly included in the focus are certain economic, ecological and social issues as identified in the previous section. Especially the environmental impact is noted important by the literature. For the environmental impact, the cumulative effects of a large number of wind turbine parks are still uncertain, and other, field-specific research is necessary. However, the initial results are positive. The mentioned issues concerning permit procedures, financial support and offshore grid will have an impact on the occupied surface and locations for offshore wind, which can be used for discussions and the comparison of paths along social and ecological values of desirability in decision making. The GDR results mention economic factors as the level playing field and relative price of offshore wind. A proper investigation would require the modelling of the entire electricity market. For this research the electricity price and investment costs will be included as an input instead, and will be taken into account in the investment decisions of the (relevant) agents.

The focus for the model has been set to:

- Permit procedures,
- Financial support,
- Layout and timing of an offshore grid,
- The availability of resources, specifically the wind turbines,
- Innovation of wind turbines,
- Investment decisions of project developers.

The topics are of course interrelated, as they are a part of a socio-technical system as already mentioned. This chosen focus of the topics leads to a selection of the most relevant target variables from the list in table 4.9. The target variables from the GDR give a direction for the development of the model, although not all variables mentioned will be output of the model. Because the system represented in the model is delineated, some should be considered as input to the model, not as output. Relatively straightforward target variables (as output) are the implementation speed and the subsidy expenditure as comparison variables for the different simulated paths. An example of a target variable from table 4.9 used as input for the model is the electricity price, as the electricity market is not modelled. In table 4.10 the chosen relevant target variables are presented. The chosen target variables will determine which output parameters the model should be able to present.

Table 4.10: The chosen target variables for the model.

Political	Speed of implementation in MW per year
	Required change of policy
	Required subsidy per kWh
	Total required expenditure
Technological	Required innovation
	Grid connection possibilities at sea
Economical	Wind parks operational and investment costs
	Total electricity production in TWh in 2020/ per year
	Investment risk

In the next chapter the model will be developed that will represent this socio-technical system. The dynamics of the model are the actions of the agents, fitting with the proposed vision of the development as micro-founded by the actions of actors. The following chapter will determine which actors should be included and how. This choice should of course reflect the delineation as presented in this chapter.

5

Development of the model

Introduction

In this chapter the development of the model is described. This chapter will describe how the socio-technical system under consideration is abstracted and simplified in the model. The sequence of this chapter is graphically depicted in figure 5.1. First, (step 1 in figure 5.1) the requirements of the model are discussed in section 5.1. The manner of identification of the elements for the model is discussed. Second, the realisation of an offshore wind park is described in section 5.2 as a step towards this identification (step 2). Third, the identification is executed (step 3), leading to the AgentModel for the agent-based model (ABm) (step 4) in section 5.3.

5.1 Steps in developing the model

5.1.1 Model requirements

For the development of the simulation model, model requirements are set to clarify the objectives for the model. These requirements serve as guidelines for the selection of elements that should be included in the model. The model requirements are as follows:

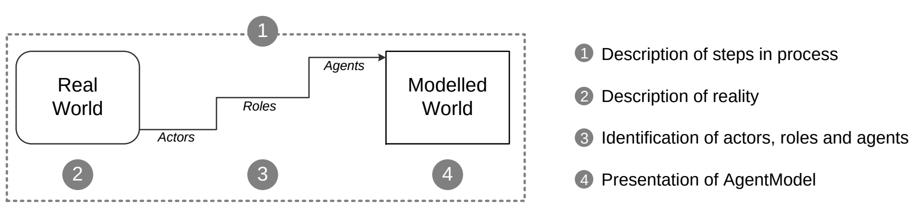


Figure 5.1: Sequence of this chapter.

- *Requirement 1*: The simulation model should include the perspectives on the implementation from actors that could have a significant influence directly and/or indirectly on the manner and speed of the implementation.
- *Requirement 2*: The simulation model is not required to be used for a micro-analysis of specific companies.
- *Requirement 3*: A park level approach is chosen: the included resources are only the main parts of a park.
- *Requirement 4*: Resources included in the model have to be either sector-specific or scarcely available.

The first requirement follows from the aim to include different perspectives in the simulation model and the approach to make a model that simulates the actions of actors to create implementation paths (chapter 1). It is the aim to test if actors can be included with different perspectives, objectives and responsibilities to simulate the changes in a socio-technical system as the actions of a society of involved actors. To limit the scope, only the perspectives of the actors will be included that can be seen as having a significant impact on the focus issues as decided in the delineation in chapter 4.

It is not necessary for the aim of this study to model actors as agents, as explained in chapter 2: a role-based approach is preferred. The emphasis is placed on the different perspectives on the implementation arising from the relevant roles of the actors, not arising from the particulars of certain specific involved actors and their view on the implementation. This is restated in the second model requirement: a micro-economic analysis of individual firms involved in offshore wind energy is not required. One could say that the field of offshore wind energy is analysed on a meso-level, on the level of the industries involved.

The third requirement determines the aggregation level of the technical part of the system that will be simulated by the ABm and the availability of resources. A high-level division of parts in a park is made: an offshore wind farm is not regarded up to every screw and bolt in a wind turbine. Only the parties involved in the main parts of an offshore wind park are considered. Such a park-level approach is assumed to give enough detail for the simulations.

The last requirement is an assumption made on how to decide what can be neglected in the choice for associated resources to the main parts such as vessels or cranes: a certain expected scarcity or specificity is required for a resource to be included. This requirement fits with the previous one as only direct suppliers of the main parts are included as actors, whereas sub-suppliers, suppliers to these suppliers of the main parts, are not: their products are less sector-specific and do not fit the park-level approach delineation. For example, the manufacturer of a wind turbine should be included as an actor, the supplier of a generator to this manufacturer is not. To take into account the availability

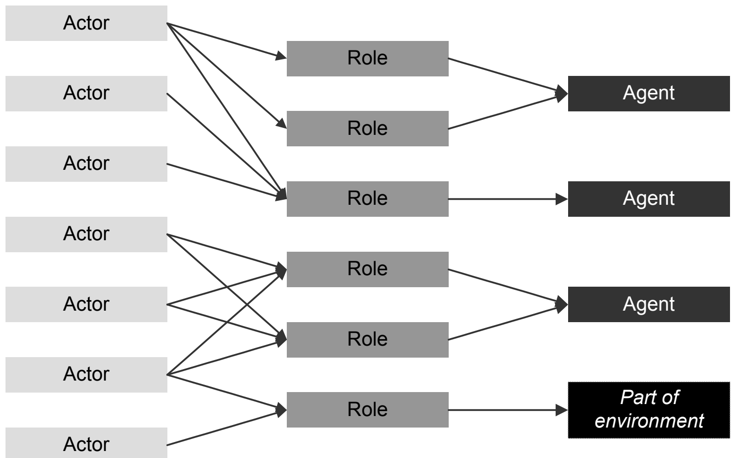


Figure 5.2: Actors are split or grouped according to their roles. Agents are formed as (groupings of) these roles.

of resources, especially investments into resources with a high asset specificity such as special-purpose vessels are of importance: these investments will only be made when the party is confident of a future offshore wind market. Sub-suppliers of resources with low asset specificity are less dependent on an offshore wind sector: the resources can be delivered to other sectors.

5.1.2 Determining the structure of the model

An identification has to be made of the roles to include in the model. The idea is that actors have roles and the roles are presented in the simulation as agents. However, neither the translation from actors to roles nor the translation from roles to agents is a 1-1 translation. This is depicted in figure 5.2.

From actors to roles

For the (delineated) socio-technical system under consideration, we want to identify which actors are involved whose roles should be represented in the simulation model. These involved actors or stakeholders (section 2.3.2) are the actors that have an interest or stake in the implementation of offshore wind energy in the Netherlands, as these actors could cooperate towards the 6000 MW target or could inhibit it.

On the one hand, an actor can have several roles, see figure 5.2. A (large) company could perform several tasks that in another case is performed by only one company. For example, project development and tendering for the contracts can be done by one company (project developer using multi-contracting) or two companies (a project developer and a main contractor). In the first case, the developer fulfils two roles: project development and tendering as a main contractor. The tendering requires special skills for risk management and detailed technical knowledge: the developer requires skills separate from the planning and selection of a site. Project management and tendering can be separated as requiring different resources (different knowledge), even though in reality the responsibility lies within a vertically integrated company or even one division or person. The separation into roles distinguishes the different core competencies and skills for the activity, and model the roles instead of modelling firms or other types of actors. This gives a clearer structure for the ABm while keeping in check with reality.

On the other hand, several actors might fulfil the same role, but model requirement 2 states that the model will not include a micro-economic analysis for these separate actors: only their roles are modelled. One role type will be modelled to represent several different actors. For instance, if two actors represent similar interests, they fulfil a similar role and they are not incorporated as separate roles: they 'play' the same 'role' in the implementation, they share the same rights and responsibilities. This does mean that the different perspectives on the implementation will be incorporated, based on the roles and not on the specific actors involved. Certain goals or interests of actors performing a similar role are not taken into account, e.g. an idealistic project developer will not be differentiated from a project developer with purely economical reasoning.

From roles to agents

Not all roles will be modelled in the same way: not all roles will be modelled as agents. The manner of interaction with the other roles determines how roles will be modelled: some roles only have a one-directional influence instead of interaction with other roles and these roles are modelled as a part of the environment of the agents. The terms passive roles and active roles are introduced here to help make this distinction.

Grimble and Wellard made the distinction in *passive* and *active stakeholders*, where active stakeholders are those who affect (determine) a decision or action, and passive stakeholders are those affected by this decision or action in a positive or negative manner [98]. Passive stakeholders are not directly involved in the implementation, but their interests are affected by it. A similar distinction can be made in *active roles* and *passive roles*. Active roles are defined as the roles of active involvement in the physical implementation, such as drilling a foundation, project development or transporting blades. Passive roles are defined as the roles actors fulfil to defend certain interests of (these or other) actors affected by the implementation. The actors in passive roles set conditions on the implementation staking out how they deem the implementation could be acceptable to them. The passive roles have an interest in the implementation but do not take active part in the physical realisation of offshore wind parks. For example, the representation of shipping interests is a passive role, as it does not involve an active involvement in the physical implementation but the defence of the interests of shipping companies for good shipping routes and shipping safety.

The term passive only reflects the actors' actions in the physical implementation itself: in the condition-setting, the actors in passive roles could be very active: e.g. lobbying, objections in consultation procedures, protests.

In the ABm, the active roles will be represented as agents, whereas passive roles are considered part of the agents' environment. The division of the passive and active roles into agents and environment is illustrated in figure 5.3. The reason for this is as follows.

The active roles are in high dynamic interaction with each other, making transactions, creating resources. The actions of the passive roles are more a one-way street: they set the conditions for the active roles when an implementation is acceptable (to the passive role). The interaction of the passive roles with other roles is therefore limited (see figure 5.3. Because of the limited dynamic interaction of the passive roles, these roles will be modelled as part of the environment of the agents. One can say that the active roles are interacting, making transactions, in an environment with elements (the passive roles) that set conditions on these (trans-)actions. The agents are therefore influenced by their condition-setting environment, but they have no or only limited influence on this environment. Modelling the passive roles as part of the environment of the agents (the active roles) will reduce the modelling time, as it will limit the amount of agents that will need to be designed, without neglecting important interactions.

It should be noted that the environment of the agents is not just formed by the passive roles, it will also include the external factors: issues that influence the implementation in a positive or negative way. The agents are influenced also by these elements, but the agents themselves have no or only limited influence on these elements. So the external factors and the passive roles have a similar impact on the active roles as agents. Examples of such external factors are the price of oil and European regulation on CO_2 emissions[1].

5.1.3 Identification of the model elements

From figure 5.2 it can be seen that for the selection of the elements of the model three steps have to be taken:

1. Identify the actors involved,
2. Identify the roles they fulfil,

[1]Note that what can be considered external is a consequence of setting our actors as the stakeholders of offshore wind energy deployment. As technological and socio-institutional change is considered micro-founded by the actions of actors, the price of oil can be considered to be determined by the actions of actors.

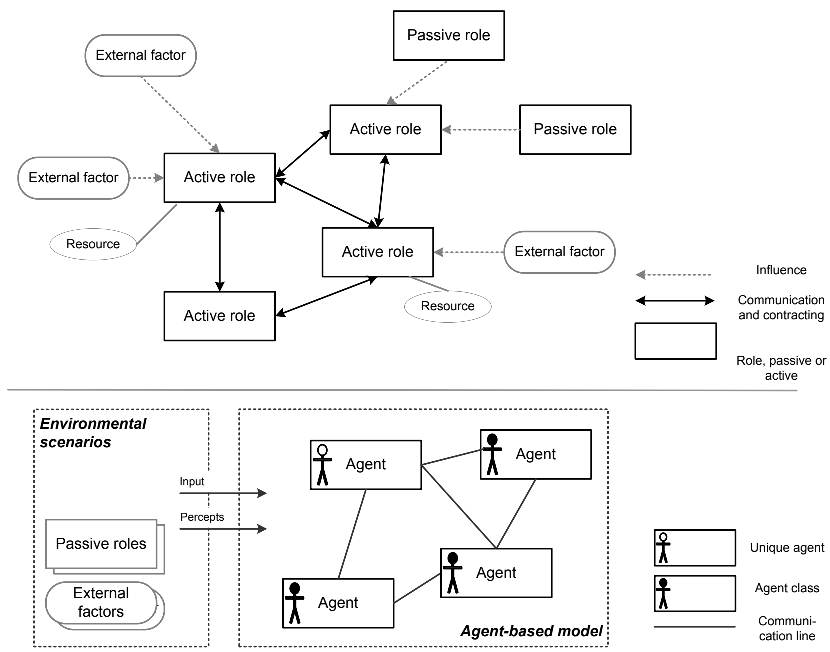


Figure 5.3: Basic system representation showing the modelling of active roles as agents and environmental scenarios depicting the passive roles and external factors. Above the line the identified role are depicted in relation to each other and the external factors. The arrow shows a direction of influence or transaction between roles. Underneath the line the representation of the roles in the agent-based model is shown: the agents are communicating, but influence by the environment formed by the external factors and the represented passive roles.

3. Select the roles or group of roles to be modelled as an agent or elements of the agents' environment.

In the methodology in chapter 3 these steps were given as the actor analysis, identification of the roles and agent selection (see figure 3.5).

An actor analysis is more an art than a science, as there is no check possible that all 'required actors' are actually included. Some guidelines for an actor analysis are given by Enserink [69]. For the actor analysis, Enserink states that relevant actors generally belong to one of four basic categories of actors: governmental organisations, business and industry, interest groups, and non-organised groups or 'society'. To identify these relevant actors he suggests starting with the following five main questions:

1. Who are actively involved?
2. Who might become actively involved at some stage?
3. Who has resources important for the problem?
4. Who has authorisation over possible problem-solving or problem-creating situations?
5. Who might not become actively involved but is affected by the implementation?

Interviews and literature are generally used to identify the actors. Actors identified following the first three questions are the actors typically concern actors from the category business and industry, as these are the companies that are actively implementing offshore wind parks. These actors have been described before as actors in active roles. The actors related to the fourth question are the actors that have some authorisation over the manner of implementation, active stakeholders as legislators or regulators, and the fifth question concerns actors in passive roles. So the question becomes how to find the actors in the passive and active roles?

Using the project as the starting point

An actor in a clear active role is the project developer. The developer initiates new projects and is therefore involved in many aspects of the creation of an offshore wind park *and* in the achievement of the 6000 MW target, as this is the total installed power of a collection of parks. His transactional environment[2] is formed by the other actors that the developer deals with in transactions in all phases of an OWF; e.g. supply contracts, consent and subsidy requests. In the transactional environment the organisation is a significant player and it can

[2]The terminology of *transactional* and *contextual environment* was introduced by Van der Heijden in the field of scenario planning [103]. In [103], an organisation is thought of as located in a transactional environment, which in turn is placed in its contextual environment.

influence outcomes as much as it is influenced by them. This transactional environment is formed by the actors that are or will be actively involved, by action or resource, that are in direct or indirect contact with each other and that are dependent on each other to a certain extent in a principal-client relationship: the actors in active roles. As stated in requirement 3, the transactional environment is demarcated by focussing only on the main parts of the park.

The transactional environment lies in a *contextual* or *condition-setting* environment, and is formed by the organisations that have an influence over the original organisation. In the contextual environment, the organisation has only limited or no influence while the organisation is greatly influenced by this contextual environment. This contextual environment can be seen as setting the conditions that constrain or support the organisation in transactions of the organisations in the developer's transactional environment. This condition setting environment is formed by the actors in passive roles.

The above relates to the manner at which actors in the real world will be identified. The developer and its transactional environment can be found by examining the project structures and contracting. The condition-setting actors ('the contextual environment') are actors involved in consent procedures (e.g. in consultation processes), lobbying, etc.

Therefore the actor analysis is performed in two parts. First, to find the active actors, the organisations actively involved now or in the future with certain resources important for the implementation, are identified by examining the contract structures and supply chains. For a clear view on the active roles, this part starts with a look at the physical realisation of an offshore wind farm in general and then several cases in particular to identify the main parts, and the main actors and their roles.

Second, the condition-setting actors, the organisations affected by or with some authority in the implementation of OWE in the Netherlands, are identified by examining the consent procedures and governmental policy, legislation and regulation concerning offshore wind energy. For the passive roles, the relevant government policy, legislation and regulation, and consent procedures are examined.

Following the delineation and the attributes of the actors (their power, means and resources) a selection is made of the relevant roles. The relevant roles are translated to agents and their environment in the agent model.

5.2 Offshore wind energy

In this section, offshore wind parks are discussed. First, a short general overview is given of offshore wind parks. Second, several cases are discussed to show the contracting between the different involved parties and third the relevant government policy and consent procedures (including consultation) are discussed.

5.2.1 Offshore wind parks

An offshore wind park consists of offshore wind energy converters and a grid connection to shore. The wind energy converters used so far in parks are horizontal-axis wind turbines, consisting of a rotor, nacelle and support structure (see picture 5.4). The rotor consists of the blades and the hub that connects the blades to the nacelle. The nacelle is the box on top of the tower. In the nacelle, the main shaft of the rotor is connected to a generator to generate electrical power. Usually a gearbox translates the low speed of the main shaft to a higher speed before the hook-up to the generator, but in some offshore wind turbines the gearbox is not present (the direct-drive turbine). Electrical power is usually transformed to a higher voltage at the turbine to reduce electrical losses.

The nacelle sits on top of the support structure consisting of the tower and the foundation. The foundation is usually a partly submerged structure of steel or concrete, such as a monopile or a jacket structure. A transition piece can be used to connect the foundation to the tower. This transition piece also has the boat landing and access platform for maintenance crews and J-tubes to lead cables from the tower into the water.

The cables from the turbines (the 'infield' or 'inter-array' cables) are gathered and the power is transported to shore by export cables: dug-in/entrenched sea-cables. If the park is far offshore, the infield cables are first connected to an offshore transformer station where the voltage is increased before the power is transported to shore to reduce electrical losses. At very far distances (at about more than 70 km) AC/DC converters are added to convert the power to DC to reduce losses[3]. The (AC or DC) sea cables cut through the dunes or dykes at the coast. They connect directly to a high voltage station, which feeds the power into the high-voltage transmission network, or first to an onshore transformer station (in case there was no offshore station) and/or DC/AC converters.

5.2.2 The realisation of an offshore wind park

A park goes through several phases from conception to decommissioning. The following description uses information from literature and interviews ([97], [89], [167], [208], [247], [188]). One can distinguish six phases: the planning phase, the procurement phase, the construction phase, operation and maintenance (O&M) phase, re-powering phase and the decommissioning phase.

[3]Losses are higher for AC cable transport, but AC/DC converters are expensive.

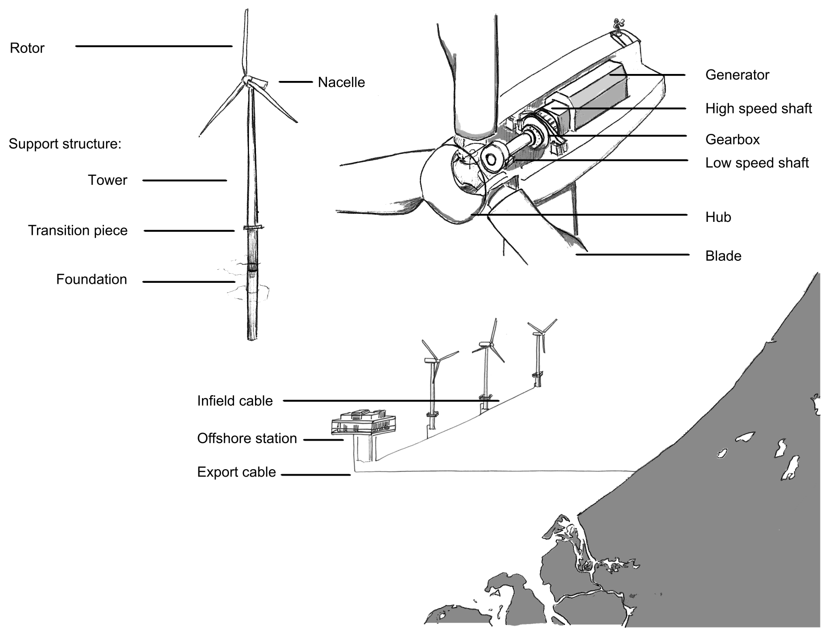


Figure 5.4: Park, turbine and nacelle zoom-in.

In the planning phase, a project developer looks for a good site for a new park, makes an initial design and applies for permits for all parts of the project. For this, the developer gathers information from main suppliers and the grid operator for the time-planning of the project and grid connection. He contacts consulting agencies for environmental and technical studies, for activities such as an environmental impact assessment and geotechnical surveys [97]. This information is used in the permit requests, including an Environmental Impact Assessment (EIA).

After consent, the procurement phase starts in which all the contracts are made for the construction of the park. With a utility, a developer closes a contract for the electricity generated by the park: a Power Purchase Agreement (PPA). Usually a PPA states the agreed price per delivered kWh the operator of the park receives from the utility. The utility then trades the electricity on the market. For the realisation of the park, contractors are required for the different parts of the park.

Two ways are common for the contracting of the construction: multi- contracting or turnkey contracting ([258], [117], [89]). In multi-contracting, a developer closes contracts with contractors for the different parts of the park. In this case the developer negotiates the price and risk division with each subcontractor. In turnkey contracting the developer closes an Engineering Procurement and

Construction (EPC) contract with a main offshore contractor, where selection is usually made by a tender process. This main contractor makes the subcontracts with subcontractors for the different parts of the park. The multi-contracting approach is possible if the company developing the park has enough expertise in project management of an offshore project to manage the division of risks and write the detailed technical requirements. Such risks include delays due to bad weather conditions for operations. Subcontractors are usually invited to tender. After the tendering for the contracts, negotiations start with the winner of the tender process for the final details. When agreement has been reached, this phase ends with the financial close, where all contracts are signed.

In the construction phase, all parts of the park are delivered to the harbour, the last onshore assembly is done and the parts are lifted to a vessel, transported offshore and installed[4]. All suppliers and others contractors for the park are included in this phase. In the final commissioning of the park the transfer of power from all the turbines to the onshore high voltage grid is realised. After final commissioning, the operation phase starts.

During the operation phase, the park is monitored, serviced and repaired by O&M crews, by periodic maintenance and unscheduled repairs. For major overhauls contractors have to be contacted [97]. It could be possible to repower the park by placing new turbines on the support structures and reusing the marine cables. This requires designing the support structures for a longer lifetime and a good compatibility with newer turbines. By 2012 there was no experience with repowering offshore, as the oldest parks in the North Sea are constructed in 2001, and it is not expected that the support structures designed for today's turbines will be compatible with the turbines in 2030.

After its lifetime, the park is decommissioned. The permit includes an obligation to remove everything from the seabed, but this might come down to cutting the foundation off at or below the seabed as is the practice in offshore oil and gas ([115], [196]). No parks have been decommissioned by 2010, but it is expected that this will involve the installing actors in the construction phase [157], [158]. In table 5.1 the main phases of the park are given with a summary of the main actors involved as mentioned in [97], [112], and [89].

5.2.3 Cases for contracting for offshore wind parks

To further identify the active roles and their interactions in the implementation of offshore wind parks, six cases are examined. The six cases are six existing offshore wind parks in three different countries: the Netherlands, the United Kingdom and Denmark. The parks are chosen for their size (at least 50 MW),

[4] The time-line of this phase is discussed in chapter 6.

Table 5.1: Main phases of an offshore wind project and the actors involved. *Source: ([97]), [258], [112])*

Phase	Main actors involved
Planning	Project developer, governmental organisations, consultants, main suppliers, societal groups.
Procurement	Project developer, main contractor, subcontractors for installation, transport and installation of main parts
Construction	Manufacturers, harbour managers, subcontractors
Operation & maintenance	Operator, O&M crews, harbour manager
Re-powering	Project developer, main contractor, government, subcontractors
Decommissioning	Main contractor

a diversity in countries, a diversity of contractors[5] and the availability of information about the contracting of the parks. All the parks were operational in 2008. The six projects' main parameters are summarised in table 5.2.

Netherlands

The two Dutch parks are Offshore Wind Farm Egmond aan Zee (OWEZ) and the Q7[6] wind park, later renamed the Princess Amalia wind park (PAWP). PAWP was licensed first, even though OWEZ was constructed and commissioned before PAWP. Two companies were contracted for the construction of PAWP: Vestas as the EPC contractor for the turbines (blades, nacelle and towers), and Van Oord as the EPC contractor for the other parts [247].

The OWEZ park is a demonstration park, its site was selected by the Dutch government and a tender for the project was won by the Nuon/Shell joint venture Noordzeewind. Bouwcombinatie Egmond, a joint venture between Vestas and Ballast Nedam Infra, was contracted in turnkey contract. The construction was divided between the two partners: Vestas had the responsibility for the turbines and towers supply, while Ballast Nedam handled the installation and the supply of the foundations [247].

[5]Especially in the parties that delivered the wind turbines, since there are only a limited number of companies supplying offshore wind turbines at present.

[6]Q7 was first named after its location, at box Q7 in the North Sea according to the box-division as prepared for oil and gas licenses in the Mining Law.

Table 5.2: The 6 chosen cases of offshore wind farms. *Sources:* ([108], [89], [186], [67], [167], [187], [76], [75])

Name	Country	Turbine	Installed power [MW]	Year operation	Distance [km]	Depth [m]	Area [km2]
OWEZ	NL	Vestas V90	108	2006	10-18	18	27
PAWP	NL	Vestas V80	120	2008	23	19-24	14
Scroby Sands	UK	Vestas V80	60	2004	2.5	3-12	10
Burbo	UK	Siemens 107	90	2007	10	1-8	10
Horns Rev	DK	Vestas V80	160	2002	14-20	6-14	24
Nysted	DK	Bonus 82.4	165.6	2003	9	6-10	24

Denmark

The Danish parks included here are Nysted and Horns Rev. In 1998 the Danish government obligated the two electricity suppliers, Elsam and Elkraft, to build offshore wind parks of a combined capacity of 750 MW [186]. In 2002, this Plan of Action was reduced to two wind farms of 160 MW and 158 MW: Horns Rev and Nysted. Both projects used the multi-contracting approach. In both parks, a transmission system operator (TSO) was responsible for the construction and ownership of the grid connection up to the offshore station, while a utility was responsible for the park, including the infield cables.

The Horns Rev park was to be built by Elsam and Eltra, a TSO. Eltra[7] constructed and owns the transformer station and grid connection [186]. Elsam hired a turbine contractor, a foundation contractor and a cable contractor (for the infield cables). Elsam had to come to an agreement for compensation with fishermen [89], and the Danish government managed the consultation process with other external groups. The park was commissioned in 2002 as the first offshore wind park in the North Sea and it is thereby the first park under harsh offshore conditions.

Nysted, commissioned in 2003, is located in the more sheltered waters of the Baltic Sea. As Horns Rev, the project was cut in two pieces: SEAS Distribution handled the grid connection and a cooperation of Energi E2, DONG and Sydkraft handled the park and internal grid. The wind turbines are placed on gravity based foundations as the waters are shallow. Experts rated Nysted as an 'exemplary' project in planning [89]. Horns Rev is placed in harsher conditions and experienced problems with its parts, but some problems also arose in planning. For the construction phase, the wind turbine contractor had hired too little harbour space, and therefore it was only possible to transport a few

[7] Merged into Energinet.dk.

nacelles and towers at a time.

United Kingdom

In the United Kingdom, the government writes out tenders for offshore wind parks in rounds. In each round, several developers state the required production subsidy for their park and the cheapest parks are selected. A developer receives[8] an Agreement for Lease, giving him sole right to apply for a permit at this location. Within a specified time, the developer should obtain the permit and start construction. By organising these rounds, the British government has control over the maximum amount of subsidy spent on offshore wind, as well as some control over the locations since preference areas are stated for the rounds.

Scroby sands is one of the Round 1 wind parks and it is the third offshore wind park in the UK, after Blyth of 4 MW and North Hoyle of 60 MW ([76], [60]). It is owned by E.ON UK Renewables Offshore Wind Ltd (EROWL) who selected Vestas Celtic for an Engineer-Procure-Install-Commission (EPIC) contract by tender. Other contracts were closed with parties for cable supply, onshore cable installation and onshore cable connection. Scroby sands has no offshore transformer station.

Burbo Bank is located in the Liverpool Bay, and was commissioned in July 2007. It is also a Round 1 wind park. SeaScape Energy hired a turbine contractor, foundation contractor and cable contractor for infield and export cables. It includes no offshore station due to its proximity to the coast.

5.2.4 Project structures for the cases

For all six projects a project structure is made, showing the contracting and subcontracting in a project by naming the companies involved in the project and their tasks. Examples of general project structures are given in figure 5.5, showing the manner of depicting the parties involved in a park and the type of activity. The examples show both a multi-contracting case and an EPC or turnkey contracting case. In appendix B the project structures of the six cases can be found. These are made to give a clear view on the contracting structure to help to make a generic contracting scheme for offshore wind parks as a single simplified version for the model.

The project structures show there are many contractors and subcontractors. For example, at PAWP, Van Oord was contracted as an EPC contractor by the owners of the farm, and Van Oord in turn subcontracted 7 other companies, e.g. Bladt and Smulders. Both turnkey contracting and multi-contracting are present in the six project cases. In the case of turnkey contracting, the project structures show that a main contractor is either an offshore contractor, a wind

[8] Or read: is allowed to buy.

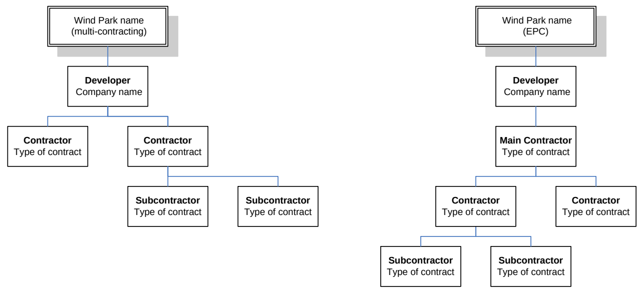


Figure 5.5: Examples of simplified project structures: on the left a multicontracting approach, and on the right an Engineering Procurement Contract approach.

turbine contractor[9] or a joint venture of both. The subcontractors of the main contractor mainly deal with the supply and/or installation of the parts of a project. Some of these contractors hire subcontractors for a part of the received tender, for instance a supplier may hire an installation company.

An example of this subcontracting is the wind turbine contractor. In all six cases the wind turbine contractor is responsible for the supply, installation of the turbine and a five year maintenance contract. The wind turbine contractor is a wind turbine manufacturer that makes arrangements for the installation of the turbines with an offshore installation company. It is expected that in the future this form of contracting will continue due to the possible damage to the turbine during installation: in this way liability is more straightforward for the main contractor and the turbine supplier [247]. Other forms are possible, for instance the company BARD can supply their wind turbines and also offers to install the entire park [20]. However, for a generic contracting scheme, the wind turbine supplier hiring an installation contractor is a suitable simplification.

5.2.5 Supply chain-based tables for the cases

By looking at which parties were contracted for which part of the project (for the construction phase) for all the six cases, it is examined if a simplified, generic contracting scheme can be made for the model. For each main part, it is checked in the project structures who was contracted by the main contractor (or developer in the case of multi-contracting) for each activity and who was subcontracted to perform the actual task.

To present the contracting parties in the six cases, a graphical depiction to capture all activities is used, which has been named Supply Chain-Based Tables (SCBT). First, for all identified main parts the activities in the supply chain

[9] A wind turbine contractor denotes a contractor who among its activities has the design and manufacturing of the turbines.

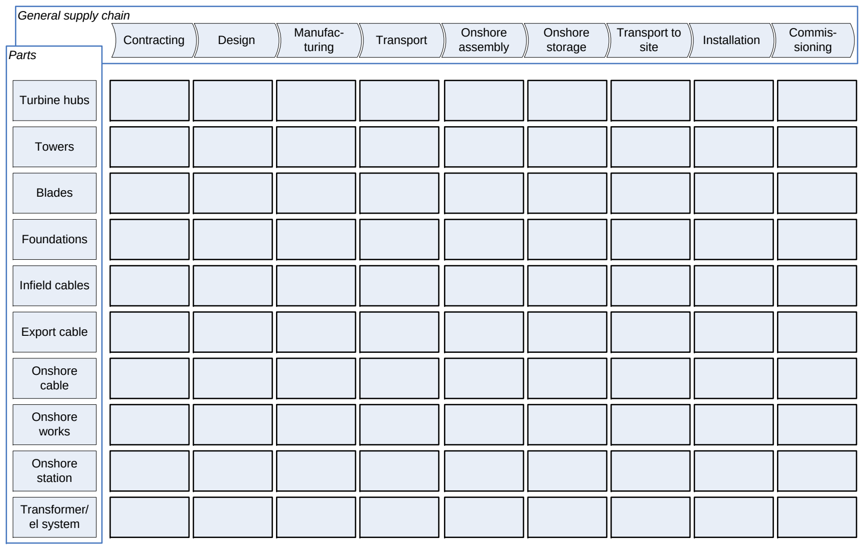


Figure 5.6: The general supply chain-based table.

are identified. Second, the contracts made by the main contractor with parties for these activities are identified (with the help of the project structures): e.g. the contracts with the turbine contractor, the foundation contractor and the foundation installation contractor. A contractor can have a subcontractor for an activity, so not all activities are need be performed by the contractor himself. Third, these contractors are filled in in the SCBTs.

The SCBT format is shown in figure 5.6. The first column shows the main parts named in subsection 5.2.1: the turbine, consisting of the nacelle, blades and tower; the foundation; and the electrical system, consisting of the infield, export and onshore cables, an onshore or offshore transformer station and the onshore work such as the connection to the national grid high voltage station. The first row are the activities in the supply chain. By filling in the boxes the contractor for the part in that row and activity in that column, the SCBTs show the parties involved in the different activities of the construction of a wind park.

The supply chain has been set up as a general supply chain for all main parts, but some activities may not be relevant for certain parts. In filling in the SCBTs, effort is made only for the relevant activities. For example, transport is not included for most parts. Transport by sea is often done by simple barges, and based on requirement four (resources taken along in this study have to be scarce or specific in a certain degree) are not considered in this study.

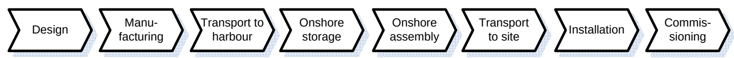


Figure 5.7: Activities in supply chain for the wind turbine parts.

For each part, the required activities are first examined as they are contracted by the main contractor (which can be the developer in a multi-contracting approach). In other words, the supply chains of the different parts are examined, as a part travels from design to commissioning offshore. The parts have different activities in their supply chains.

Supply chains

For the parts of the turbine, the parts follow similar activities as depicted in figure 5.7. The nacelle, blades and tower are designed, manufactured and transported to a harbour close to the site. Here, the nacelle and blades are assembled together: two or three blades can be connected to the hub, so it can be installed in one piece offshore. It is also possible that the entire turbine is assembled onshore. The activities of the actors in the supply chain of these parts follow therefore a pattern as shown in the figure 5.7. Transport on land can entail specialised vehicles, but the transport is done non-sector-specific resources. Decommissioning is not added, as this is not contracted in the procurement phase. As only the main parts are taken into account, the assembly of the nacelle is not regarded.

The foundation can have several forms, the choice depending on the site conditions: the monopile, the gravity-based structure (GBS) or jacket structure are prevalent. In five of the project cases, the monopile is used; only in the Nysted park GBS are used. For the monopile and a transition piece, the list of activities of the actors in the supply chain are as depicted in figure 5.8 A. For a GBS, the activities look like list C in figure 5.8, depending on whether the GBS is completely created on the harbour site. For jacket structures the activities look like list B. For foundations, the transport to the harbour usually not uses the same vessels, and transition pieces are usually transported twice: from the factory of the subcontractor for the steel tubes to the next subcontractor who adds the secondary steel (boat landing, platform) and then to the harbour. But this transport is usually part of the supply contract for the foundations and transport is mainly done by simple barges. Therefore no effort has been made to fill in the transport of foundations in the SCBTs.

For the electrical system, a park further offshore can include an offshore transformer station, while a park closer to the coast could save money by placing the transformer station onshore. As no parks (apart from the OWEZ demons-

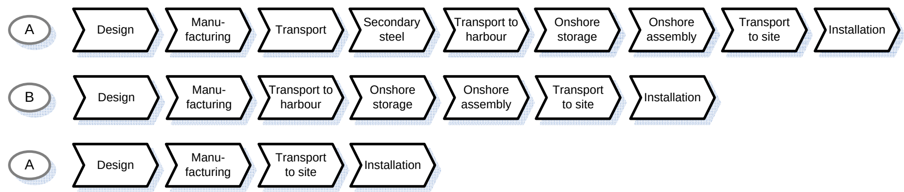


Figure 5.8: Activities in supply chain for the foundation.

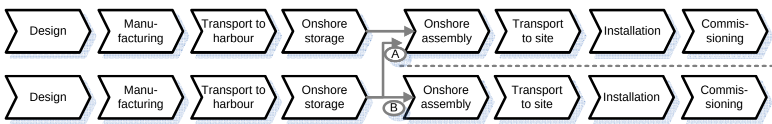


Figure 5.9: Activities in supply chain for the offshore transformer station, if present in the park.

tration park) will be build in the 12-mile zone, it is to be expected all parks will require an offshore substation. The supply of the offshore platform is often a separate contract from the supply of the transformers. In some cases they are assembled together onshore in the harbour (alternative A). The foundation for the platform is included in the foundation contract for the wind turbines in all examined cases. The offshore platform and transformer[10] require the activities in figure 5.9.

For all the cables (infield, export and onshore cables), the activities are represented in figure 5.10. The transport of the inter-array cables to the marshalling harbour can be done by simple barges, but the export cables are too wide in diameter to be bend onto reels and a specialist vessel is required that picks up the cable from the factory and transports it to the site directly. The onshore station follows a similar activity list as the cables.

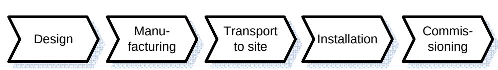


Figure 5.10: Activities in supply chain for the infield, export and onshore cable, as well as the onshore transformer station of present.

Simplified contracting scheme

The resulting SCBT's are given in appendix C. Two main simplifications are made to go towards a general contracting scheme: parts are grouped, and acti-

[10]The station includes other electrical systems, such as shunts. These are included in the SCBT if it clarifies the SCBT, but filling in these contractors has not been given priority.

vities are grouped.

Some of the mentioned parts are always contracted together by the main contractor. For instance, the nacelle, blades, hub and tower are combined in one contract with the turbine contractor in all six cases. This turbine contractor is a wind turbine manufacturer in all six cases. Other examples are the infield cables and offshore connection sea-cables, they are usually supplied by the same contractor. Five main parts can be distinguished as a combination of the parts that are contracted to the main contractor (which can be a developer) in one contract:

- Wind turbine (consisting of the nacelle, blades and tower),
- Foundation (including transition piece),
- Transformer station,
- Cables (infield cables, export cable),
- Onshore work (onshore cable and connection).

Some of the activities can be combined, as one contract is made for several activities. For instance, the main contractor makes a supply&install tender for a turbine contractor. However, some of the contracted activities can then be subcontracted to subcontractors: e.g. the turbine contractor does not do all activities himself, but subcontracts activities, e.g. blade manufacture can be subcontracted[11] and turbine installation is subcontracted in all cases, as wind turbine manufacturers do not generally have wind turbine installation vessels[12].

In the SCBT's, one can see that the contractors to the main contractor are either suppliers or installation companies. The main contractor either writes out a tender for the supply and installation of a part or for the supply and installation separately. Other activities, e.g. design and transport, are subcontracted by the supply and installation contractors. Therefore five possible contractors can be distinguished that answer to the tenders of the main contractors:

A Contractor that subcontracts installation to a subcontractor (e.g. wind turbines),

B Contractor that subcontracts the supply of the part (e.g. foundations in case OWEZ),

C Contractor for a supply & installation contract that perform the activities themselves,

D Contractor that subcontracts supply and installation (e.g. foundations in case Horns Rev),

E Contractors for supply and installation are hired separately by the main contractor (e.g. foundations in case PAWP).

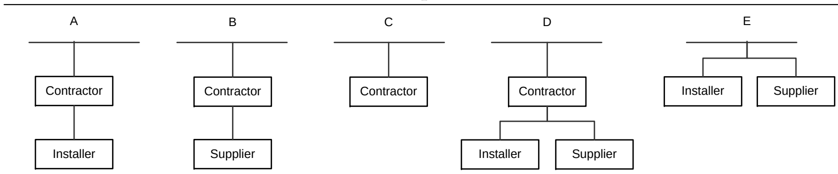
[11] Not all wind turbine manufacturers manufacture their own blades within the company.

[12] There are counter-examples: wind turbine manufacturer BARD has the installation vessels, as they want to vertically integrate all activities for a project within BARD.

Table 5.3: Contracting forms. Note: The main contractor (MC) can be a developer, another company or a joint venture. The MC can perform one of the tasks himself (as a contractor of himself).

Part	OWEZ	PAWP	Scroby	Burbo	Nysted	Horns Rev	Dominant
wind turbine	A	A	A	A	A	A	A
foundation	B	E	D	D	D	D	D
offshore cables	D	D	A	A	A	A	A
onshore works	D	C	C	C	C	C	C
offshore station	-	A	-	-	D	A	A

Explanation



For the six cases, we look at which kind of contracting is dominant for each part and activity. The results are shown in table 5.3. The table includes a graphical explanation of the five contracting structures. In some cases a dominant form is clearly visible, for some parts there are several prevalent contracting structures. The choice for the dominant contracting form to the main contractor is presented in the last column of table 5.3, e.g. for the wind turbine the chosen dominant form is form 'A', where a contractor makes a design&supply&installation contract with the main contractor but subcontracts the installation.

For the model, a simplified contracting scheme can now be made using the dominant contracting forms stated in table 5.3 and the five parts. Certain activities will not be taken along as activities with separate contracts for the model, as they are included in other contracts or concern resources with high availability. For example, activities such as transport and onshore assembly are assumed to be included in the contract to the main contractor, as seen in the contracting in the cases. Also, the availability of required resources for transport (e.g. barges) is reasonably high, while the resources of other actors in the supply chain of the various main parts are more restricting for the timing of large-scale implementation due to their availability ([81], [89], [78]) (model requirement 4). The focus is therefore put on the suppliers and installers of the main parts, the harbour manager (for the availability of harbour space) and O&M contractors. Under these assumptions, the simplified contracting scheme is depicted in figure 5.11.

This simplified contracting scheme shows a generalised view on which actors are involved in a project, and will be used to identify actors in active roles in section 5.3.1. Although not all case projects fit exactly in this scheme, most can be fitted to this in a reasonable degree, as could be seen from table 5.3. A simplification of reality is required to be able to model and simulate the development of offshore wind energy in a generic manner.

5.2.6 Government policy and the condition-setting environment

Several contractors in direct or indirect contact with the developer have been identified. The developer is also in contact with and influenced by the national government, and local authorities and local groups. There are actors that want to influence the implementation (of a certain park or offshore wind in general) to protect their interests. This influence can be exerted through the local and national government, as the government makes policy affecting offshore wind parks. Therefore, by examining government policy another group of actors can be found consisting of a few actors in active roles, but especially the actors in passive roles: the condition-setting environment of the developer (and the other actors in active roles). To identify this group of actors, governmental policy is reviewed. The three main regulatory aspects have been named in chapter 4: consent procedures, grid arrangements and financial support.

Note that the PAWP and OWEZ parks will not be representative for future parks for the permit procedures, financial support or grid arrangements. PAWP was started before the moratorium was set and was therefore allowed to continue to a permit request. OWEZ is a demonstration park and a monitoring and evaluation programme was mandatory. In the beginning of 2012, new policy still had to be set for the subsidy and permitting. The permitting procedure described here relates to the policies and regulations as in place in 2005, when a large amount of permits was requested.

Consent procedures

Several departments are involved in deciding the policy for offshore wind energy and offshore wind parks. In the North Sea spatial planning document towards 2015 (IBN2015) [143], the ministry of Economic Affairs (EZ)[13], Finance, Agriculture, Nature and Food Quality (LNV), and the Ministry of Transport, Public Works and Water Management (V&W) were involved to determine the national position on offshore wind energy in the North Sea. They concluded that the use and necessity of OWE can be considered proven, and it is therefore not required to be proven for individual projects. In a consent procedure developers can refer to the IBN2015 for the necessary statement of usefulness for offshore wind farms.

For the installation of an offshore wind farm in the Netherlands, the two most important and time-consuming permits are the permits for the Public Works

[13]The current Ministry of ELI

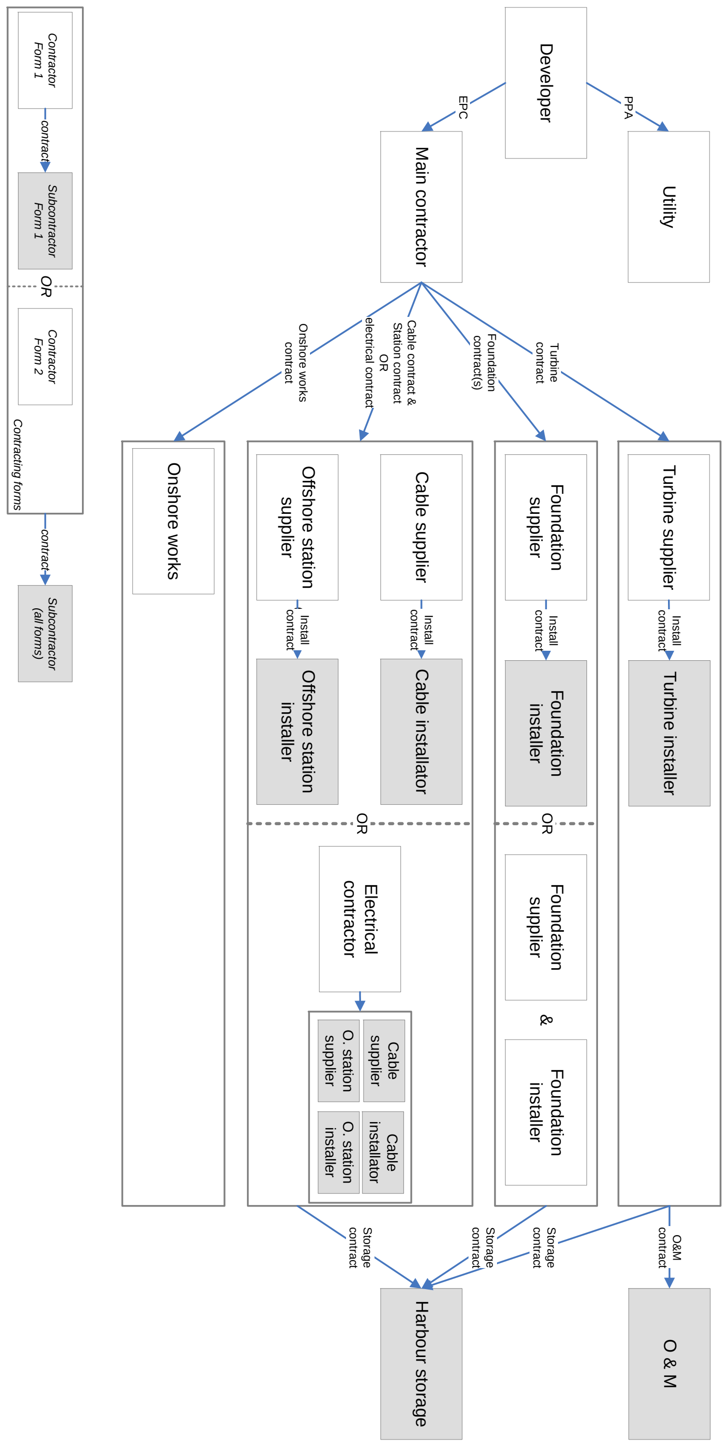


Figure 5.11: The simplified contracting scheme for offshore wind projects.

1	Offshore mining
2	Sand and grind collecting
3	Shell collecting
4	Dredging/ Seabed-excavation dump (Baggerstort)
5	Ammunition drop zones
6	Military activities and practice areas
7	Shipping (recreational, traffic, anchor zones, clearways, shipping routes
8	Natura 2000 areas
9	2nd Maasvlakte, including the Sea Reservation
10	Cables
11	Pipelines
12	Fishing (professional and recreational)
13	Air traffic, including offshore helicopter operations
14	Telecommunication
15	(Other) wind farms
16	Mussel seed collection installations

Table 5.4: Activities on the North Sea. *Source: [143]*

and Water Management Act (Wbr[14]) [150] and the Environment Law (Wm) [55]. For parks outside the 12 miles zone, permit requests submitted for the Wbr include the Environment Management Act (Wm) request, and an Environmental Impact Assessment (EIA) is mandatory for areas where impacts are considered significant. In the EIA, the impact of an offshore park in the North Sea on the environment needs to be addressed: on the natural environment and on the other users. Other users of the North Sea have been identified, see table 5.4. These are actors deemed affected by the implementation of offshore wind parks and their interests have to be taken into account.

In 2005, the new permitting procedure for the Wbr started. In this procedure, the developer sent his project initiative ('startnotitie'), to Directie Noordzee (DNZ), part of the Ministry for Transport, Public Works and Water Management. DNZ replied with the guidelines for the permit request and made the initiative public. For a permit for the Wbr, plans for construction and decommissioning had to be submitted together with the EIA[15]. Not until this request had been accepted did the developer have a claim on the location. After permit approval and the start of the subsidy tender, the project developer was given a limited term of two building seasons to start the construction [205]. In this time, the developer has to get the remaining consents (e.g. a permit for cables running through the territorial waters, permission to cross the cables through the dunes) and arrange for the attainment of subsidies. Other permits are handled mostly by local governments, for instance permits for onshore work

[14]'Wet Beheer Rijkswaterstaatwerken', now incorporated in the Water Act, the 'WaterWet'.
[15]In Dutch the 'MER', 'Milieu Effect Rapportage'.

or near-shore cables.

Grid arrangements

The grid owner TenneT is only the onshore transmission system operator (TSO); the project developer pays for and owns the offshore cables and the onshore cables connecting to the high voltage transmission grid. Studies have examined different possibilities for arrangements and regulation of the grid; see [180] and [182]. The latter study suggests a preference for transition to an offshore grid operated by the onshore TSO, mainly for consistency with the onshore situation. Changes to the grid arrangements require a change in the Electricity Act (Elektriciteitswet) and therefore require approval of Parliament and the Senate. TenneT is an important actor in possible new arrangements and as the onshore TSO might have their responsibilities extended to national onshore and offshore grid operator.

At Beverwijk, one of the main connection points to the transmission grid, bundling may be necessary, since the number of dune crossings should be limited. Other locations for hook-up are Maasvlakte and Eemshaven.

Financial support

Financial support can be given as tax incentives or direct subsidies. Direct subsidies are usually production-based, as this shows a better efficiency than installed capacity-based subsidy, which can lead to over-dimensioning of the generator as seen for instance in the Netherlands in the time of the IPW. When the moratorium for offshore wind farms was lifted in January 2005 (see 4), there were two financial support systems in place for offshore wind parks: a fiscal measure, the EIA (Energie Investerings Aftrek), and a production-based subsidy for Renewables production called the MEP (Milieukwaliteit Elektriciteits Produktie). The EIA is a fiscal arrangement for a tax deduction for investments made in energy saving and renewable energy. The Ministries of Finance and of Energy, Agriculture and Innovation (ELI) set the EIA, while AgentschapNL[16] and the Tax Office execute it. In the MEP, several renewable energy sources are supported by covering their unprofitable top[17]. In 2009, the MEP was replaced by the SDE (see 4.1). The SDE tender submissions were sent to and handled by the ministry of ELI [145].

5.2.7 Consultation

In the consent procedures, the permit authority has to balance the interests of the different stakeholders in determining approval or denial of a permit. To ensure that everybody can defend their interests, the permit request and following decision are made public and are open for consultation ('inspraak') for a certain

[16] Previously SenterNovem

[17] The MEP was set to 0.097 euro/kWh for offshore wind in 2006.

period. In the case of a concept decision ('ontwerpbesluit') for a Wbr permit, this consultation period is six weeks. The permit request and the decision are published in the Staatscourant and the documents are available at the website of the Centrum voor Publieksparticipatie ('Centre for public participation') [256][18].

In the previous section it has been discussed which authorities are involved in making the decision. The respondents show a wide variety of actors, stakeholders to the implementation. Therefore this list of respondents can be used to help identify stakeholders to the implementation, especially the stakeholders in passive roles. To make this identification, a case study is made into one of the parks, the offshore wind park Katwijk/Beaufort. This is one of the 72 initiatives placed in 2005. It is one of the parks permitted in 2009, but there was a considerable uncertainty in the process. The process included three consultation rounds. This initiative is therefore chosen for a case study.

Case consultation

In 2005 Nuon and Shell started the preparations for wind park 'Katwijk', 24 km off the coast near Katwijk in water depths of 20 to 28 metres. The park was planned to consist of 3 or 5 MW wind turbines for a total installed power of about 340 MW. WEOM, a subsidiary of Nuon, developed the site on behalf of Nuon and Shell, until Shell stepped out in March 2009. Nuon continued the development, renaming the park 'Beaufort'.

The Beaufort park site is located between shipping lanes and close to mining platforms and an anchorage area for Scheveningen harbour. For the Wbr permit request, the Katwijk site was divided into two sections. WEOM applied for a Wbr permit in 2005. The developer E-connection also placed a permit request for an overlapping site. On the 24th of November, 2006, the Wbr permit request and accompanying EIA filed by WEOM was deemed complete by the authority Rijkswaterstaat Dienst Noordzee (RWS-DNZ) [151]. The permit request was made public and the consultation process for the MER started. Several respondents reacted to the EIA-consultation. In table 5.5 the reader can find the list of respondents with a summary of their reactions.

During the consultation, a Nautical Advisory Board[19] (NAB) was formed to give advice on shipping safety. The NAB consisted of persons from the nautical sector, the ministry of VenW, a radar expert and an expert in SAMSON, a shipping-movements calculation model. Four nautical stakeholders also offered their advise out of their own accord: the Coast Guard, the Directorate-General of Transport (DGTL), Central Nautical Management of the Noordzeekanaal

[18] This was previously 'inspraakpunt.nl' [113]

[19] The 'Nautische Advies Groep', in Dutch.

Actor & Opinion
Individual (Rooseboom) The chosen turbine size does not represent the state-of-the-art. Safety issues have not been sufficiently addressed. The developer should be required to promote the development of wind turbines and share the knowledge gained.
Stichting Berkheide Coepelduijnen Respondent strongly opposes the park due to the visual impact of the offshore wind park(s), the environmental impact and the cumulative effects of all offshore wind parks. Offshore wind represents an expensive and inefficient way to reduce CO_2. Turbines of 3 MW should not be built within 40 km off the coast and 5 MW turbines should not be built within 50 km.
Air traffic control Disturbance to radio and transponder signals have not been sufficiently examined. The safety of air traffic control services can not be guaranteed if offshore wind parks are realised.
Municipality Katwijk The EIA lacks arguments for location choice. A minimum of 30 km distance to coast should be desired. The municipality wishes to be informed of the status of the park.
Productschap Vis The preference areas for offshore wind parks will seriously hinder the fishermen. The EIA lacks scientific argumentation and research into the (cumulative) effects on the natural environment. Shipping safety should be guaranteed and a comparison should be made to OWEZ.
E-Connection Because the initiative includes two non-adjoining areas, two EIA's should have been filed. The respondent misses information on the cumulative effects (e.g. morphology, water quality, other wind parks) and the incorporation of the results of other parks (e.g. OWEZ, Nysted).
Kustvereniging EUCC The damage and risks of offshore wind parks to e.g. nature and visual impact have not been sufficiently researched, and the damage and risks do not weigh against the unclear gain for the energy supply. The parks could even increase risk to the power grid (black outs). Respondent feels that it is not worth the low reward.

Table 5.5: Consultation respondents and a short description of their reactions to the EIA of owp 'Katwijk'. *Source: [151]*

Table 5.6: Respondents to decision on offshore wind park 'Katwijk'. *Source: [153]*

Nederland genootschap van insprekers[a]	Ballast Nedam
CNB Noordzeekanaal	AYOP[a]
Province of North Holland	E-Connection
Stichting Berkheijde Coepelduinen	WEOM
Zeehaven IJmuiden	

[a] Dutch Society of Participants.
[a] The association of Amsterdam IJmuiden Offshore Port related industries.

area (CNB) and the port of Rotterdam[20]. The nautical groups are unanimous in their advice: the park should not be built[21].

The main reasons for the negative advice was that it is located in a separation zone, close to helicopter platforms and close to the shipping lanes and an anchorage area. The park would negatively affect the shipping safety: a drifting ship could hit a turbine, it would limit manoeuvre space and affect visual navigation of ships. In the advice of the DGTL, almost all (72) initiatives got a negative advice: only the (11) wind parks at least 50 km off the coast meet their criteria[22].

Based on the advice of the nautical groups, the permit was denied on the basis of the negative effect on shipping safety. The calculations in the EIA using the (recommended) SAMSON calculation model (which showed only a limited to negligible effect) were disregarded. The permit request for two other initiatives were also denied on the same basis. The decision was made public on the 17th of September 2007. Nine actors responded to the consultation to this decision, see table 5.6 for the list of respondents.

One of the respondents was E-Connection, the developer of an initiative on the same site. Although E-Connection had filed their request before WEOM, their request was deemed incomplete at the 23rd of November 2006. In the 'policy rules' for the permit procedure [205] it was stated that the site would be exclusive to the developer with the first complete permit request, including a complete EIA. The disadvantage of this 'first come, first serve' policy gives a developer exclusivity at a late stage, after spending a considerable amount for an EIA.

[20] In Dutch: 'Kustwacht', 'Directoraat-Generaal voor Transport en Luchtvaart', 'Centraal Nautisch Beheer Noordzeekanaalgebied' and 'Havenbedrijf Rotterdam'; respectively.

[21] All documents are available at the website of the Centre for Public Participation [256].

[22] Two initiatives of the coast near Den Helder also fit the criteria, but the DGTL judged this area 'too crowded' for an offshore wind park to be placed without negatively affecting shipping safety [256]

Table 5.7: Consultation respondents to design decision of offshore wind park 'Beaufort'. *Source:* [153]

Zeevisserijbedrijf Post	Productschap Vis	E-Connection
Royal Dutch Watersport Union	Nautical Vision	CNB
Port of Rotterdam	Delta Hydrocarbons	Nuon
Vissenbescherming	Municipality Katwijk	Cirrus
SWNB (Foundation for Scientific Nature and Environment Policy)		

In six of the nine reactions, the respondents complained about the procedure that had led to the denial of the permit. They felt that the right balance of interests was not found in that decision, as much weight had been given to only one interest group or sector. They stated that the governmental target of 6000 MW would not be achieved if the reason for permit denial was upheld. After all, most of the initiatives are placed close to shipping routes and sites further offshore are more expensive. The developer was one of the six respondents and complained of the non-transparency of the procedure, also because a new advisory board had been added during the consultation process even after the EIA was deemed complete.

The complaints led to a second review of the permit request [153]. New research was done into shipping safety, helicopter flight safety, radar interference and environmental impact. Several interest parties were asked how the site request could be adapted to become acceptable. After this new research, the EIA and the permit for Katwijk/Beaufort were approved, under certain conditions. The main condition making the approval possible was that the site should be smaller: the southern part of the site overlapping with a new traffic separation system was excluded, as well as a small part within a 5 nautical mile radius of a helicopter platform. The decision was published and 13 actors responded to the consultation, see 5.7.

Six respondents had already been involved in the process before: the Port of Rotterdam, CNB, municipality of Katwijk, Productschap Vis, E-Connection and Nuon. One reaction was the Nautical Vision of several nautical actors, explaining their criteria for the balance of the economical interests of sea harbours, safety and sustainability. Parks should not be built in crowded shipping areas, taking into account desired growth of harbours. Parks should preferably be built on sand banks, at a minimal distance of shipping lanes of 2 nautical miles (nm), and guard ships should be present for accidents. To optimally implement offshore wind energy, the nautical vision suggested parks should not be scattered over the North Sea and wind turbines should be at least 5 MW, to ease navigation.

Two actors from a fishing background (Productschap Vis and a sea fishing company) and two environmental groups stated their concern for the impact of parks on fish, while the first two actors added the concern for the loss of fishing grounds if fishermen were not allowed in the parks. The sea fishing company felt it had not been included in the decision making. One environmental group suggested that a preference should be made for gravity based structures as foundations, since the installation of this foundation did not entail hammering noise. An oil and gas company responded that it was unclear for it what the consequences were for mining licensees if a park would be built in the licensee's box.

After the preparations started in 2005, the initial 'no' in 2007 and the final 'yes' in the end of 2009, Nuon could go into the procedure to obtain an SDE subsidy under the new system of tendering.

The consultation processes in 'Beaufort/Katwijk' have shown a variety of actors and makes clear what their interests in the implementation are by the concern they submit.

5.3 Identification of roles and selection of agents

5.3.1 Relevant actors

An initial inventory of actors involved in offshore wind energy in the Netherlands can now be made. Most actors in active roles are illustrated in the general overview, the project structures of appendix B, the SCBT's in appendix C and the generalised contracting scheme in figure 5.11. From the identified other users of the North Sea and the participants in consultation processes one can identify the involved actors in passive roles. From the description of the governmental policy, it can be seen that some government agencies can be considered actively involved in the physical implementation in dealing with the developers and utilities for e.g. subsidies, financial support and the offshore grid arrangements and therefore fulfil active roles.

No effort is made to identify all specific actors: some actors can already be grouped if they have similar objectives. Instead, a term is used that describes these similar actors. For example, in the list of involved actors, WEOM, Airtricity or Evelop are not specifically mentioned, but they are captured in the general term 'project developer'. The SCBT's and the generic contracting scheme give an initial set-up for what this term (or terms) describing a group of similar actors should be. Because of similar objectives, the actors contracted for supply or installation are termed subcontractors.

After the initial inventory, use is made of a relevance tree (e.g. [230]) to further identify the relevant actors in a systematic manner. A 'relevance tree' is a pictorial representation with a hierarchical structure that shows how a given topic can be subdivided into increasingly finer levels of detail, so a broad topic is subdivided into increasingly smaller subtopics. This is compared to the results from the interviews, GDR and literature research to see if all topics that came forth are present to obtain an as complete picture as possible.

For all identified actors, their characteristics related to offshore wind are defined based on the interviews, GDR and literature review: their *involvement* in the implementation, as the functions they perform in the implementation; their *interests* as utility or welfare they can get or lose from the implementation, the *power* they have to affect the implementation, their current *position* towards offshore wind and the implementation's *impact* on the actors as a scale from low to high. In figures 5.12 and 5.13 the results of the actor analysis are given. The tables cover a broad spectrum of governmental organisations, businesses, interest groups and societal actors with varying impact on the implementation.

The figures summarise the different stakeholders and their interests: it shows who are involved and how. Excluded from the study are the actors with a low impact (power) on the implementation or the actors outside of the scope of this research. For example, second order suppliers, suppliers to the suppliers of the identified five main parts, are not included as they are outside the scope of the (park-level) research.

5.3.2 Relevant roles

The identification of the actors is the basis from which the relevant roles are identified. The figures 5.12 and 5.13 show the actors's interests and instruments show how their roles might be grouped to form all relevant roles to the implementation and whether they can be considered active or passive roles. In section 5.1.2 it was explained that the translation of agents into roles is not one-to-one. This means for certain actors that their activities are split into separate roles, or in some cases that actors are grouped into one role.

In figure 5.11 a general contracting scheme was given: this scheme illustrates the active roles that are relevant for the implementation of offshore wind energy. Certain governmental agencies are in direct contact with developer and utilities, for e.g. subsidies or permits. These tasks are active roles of national government agencies. Policy and legislation are more external tasks, on which other actors in active roles can have little or no influence and should therefore be set as part of the condition setting or contextual environment: as passive roles. This leads to the roles as presented in the RoleModel in figure 5.14.

5.3.3 Agents and the Environment

Relevant roles are represented in the ABm: active roles by agents and passive roles as part of the Environment of the agents, together with the external factors. As a representation of the structure of the ABm, an AgentModel is

Stakeholder	Involvement in issue	Interest in issue	Influence or power	Current position	Impact issue on actor
Governmental organisations					
Min of Finance	Key role in financial policy of government, approve budgets, set investment taxes, receives gas profits	Expenditures must be balanced, budget not exceeded.	High	Monitoring	Medium-High
Min of Economical Affairs	Responsible for sustainable economic growth, by stimulating entrepreneurship, innovation and competitiveness. Also responsible for a sustainable energy household and the energy mix. Makes policy on support of RES.	Sustainable energy household; security of supply, optimal fit of RES in energy supply, diversification, emission reduction. Keep expenses in budget.	High	Supportive/ investigative	High
Min v V&W	Makes policy for North Sea. Handles Wbr permit, could define exclusion areas. Advice for bundling of infrastructure wind parks	Should not endanger safety, accessibility or liveability, either by collision risk, occupied space, shipping routes, coast & dunes. Beware of cumulative effects & efficient use of space. Regulation for more cooperation and parks outside the 12-miles zone.	High	Supportive, investigative	High
Rijks-waterstaat	Part of V&W, responsible for national infrastructures concerning roads & water, such as dunes and dykes.	Concerns for the strength of dunes or dykes.	High	Monitoring	Medium-High
Dienst Noordzee	Part of RWS, specifically for North Sea. Coordinating manager of North Sea. Manages Noordzeeloket for everyone (despite who has responsibilities)	Concerns for living sea, good shipping routes and safety for shipping. OWE should not interfere. Handles the permits. Checks if cables are still in correct place	High	Supportive, investigative	High
IDON	Interdepartementaal Directeuren Overleg Noordzee.	IDON aims to coordinate policy for North Sea within the gov.& communicate this policy to outside.	Medium	Coordinating	Medium
Parliament	Beleid rondom subsidies in uitgaven en inpassing; kosten en baten OWE	Balance costs and benefits, satisfy voters, therefore affected by social support	High	Changing (about every 4 years)	High
Min of Defence	Defence of NL	7% of NS used for defence, defence areas and parks should not conflict.	Medium-High	Monitoring	Medium-High
Min of NLV , Directie Nature	Directie Nature deals with biodiversity issues of all species in NL.	Environmental impact, F&F law	Medium-High	Monitoring	Medium-High
Grid operator	Arranges the national transmission grid: enough capacity, grid strengthening, reliability, balance costs	Integration of wind energy in the grid, possible offshore grid	Medium-high	Supportive, investigative	High
Senter/Novem	Handles subsidies	Governmental expenditure on offshore wind	Medium	Supportive, investigative	Medium
Energieraad	Advises government	Are afraid that high number of offshore wind are only possible if energy storage is available, esp. at night.	Medium	Negative	Medium
Business & Industry					
Developers	Profit margin Green image	Successful project at low risk and high profitability. Now still high risk projects	Medium	Need for lower risks.	Medium-High
Consultants	Seabed measurements, design, site data	Profits, reliable new stream of income	Low	New market possibilities	Medium
Utilities	PPA with developer, often a buy-every-kWh-produced. Joint venture with developer	Good for image, not always enthusiastic. possible RES-targets for portfolio. Have to predict their wind power.	Medium-High	Diverse: unconvinced to active	High

Figure 5.12: Actors and interests part 1

Stakeholder	Involvement in issue	Interest in issue	Influence or power	Current position	Impact of issue on actor
Offshore contractor	Now usually in turnkey project, part of multi-contracting also possible	Market party; all work. Profit, market share, reliable new market	Medium	Market should grow	High
Offshore sub-contractors	Subcontractors (manufacturers, O&M, transport, installation)	Market party; profit, market share, reliable new market. Need for lower risks, bigger markets	Medium	Market should grow	Medium
WT manufacturer	Part of subcontractors or joint venture with contractor. Deals with contractor or developer (design stage)	New future market, but needs to rise faster: small market, high risks. Onshore market now more important generally.	High	Lower risks & uncertainties; need steady market.	Medium
Harbour managers	Part of shipping and harbours. Should secure proper locations for installation	Need a steady new market with profits to make that interesting	High	Unconvinced	Medium
Insurance companies	Insure projects with profit	High technical risks leads to high insurance price. Green image as green insurer.	Low-Medium	Needs steady market & policy, proven technology.	Low
Investors (private or corporate) and banks	Invest in projects, should be successful project at low risk and high profitability	Profit, image. Risks are high and must be addressed	Low-Medium	Unstable governmental policy Technology not proven	Low
Fishers	No hindrance from parks: Keep their fishing grounds and do not scare away the fish. Safety issue with economical issue	No smaller fishing grounds No danger from collision with parks. Are still fishing in park space. Feels small influence	Medium	Condition-setting	Medium
Research institutes	Institutes, universities performing research	New research projects. Adapt design to offshore environment. Could also support other generation.	Low	Diverse	Medium
Interest groups					
Local environ-mental group	Protect the local environment of the North Sea	The fish, sea mammals, birds and benthos are influenced in a minor way, both in impact and duration. measures should be taken to minimise to insignificant impact	Medium-High: can organise the societal groups to lower social support	Supportive but condition-setting.	High
Global environ-mental group	Protect the global environment, large-scale wind will help against global warming	The local effects must weigh against the global benefits	Medium	Supportive/ Pro	Medium
Air traffic control	No disturbance.	Disturbance turbines on communication	Medium	Condition-setting	Medium
Other users	Procedures, assignment of areas by government.	Areas fin NS, for e.g. sand collection, dredging.	Medium		Medium
Shipping and harbours	Want no hindrance of parks on ships	Distance to shipping lanes, safety, No parks close to runways	High	Condition-setting	Medium-high
Society					
Consumers	Consumers of electricity, tax payers. Social support affects governmental support	Security of supply Low energy prices and taxes (gov. expenditure)	Collectively High, but unorganised.	Varies, now mostly indifferent to pro	Medium-High
Coastal municipalities	Inhabitants of coastal areas, visual hindrance day/night. Closed beaches for construction. Dead animals on beaches	Want no Visual hindrance, noise hindrance. Hindrance beach and roads for cables. Health of North Sea	Cooperation between parties in laying cables	Parks close to shore	Low-High (Dependent on distance)
Tourism	Tourists moving to another beach due to visual hindrance or closed beaches (work in progress)	Possible loss of revenue	Medium	Uncertain	Uncertain
Anti-Wind	Protesting against wind energy, legal procedures	Against wind energy	Low-Medium	Against	Low

Figure 5.13: Actors and interests part 2

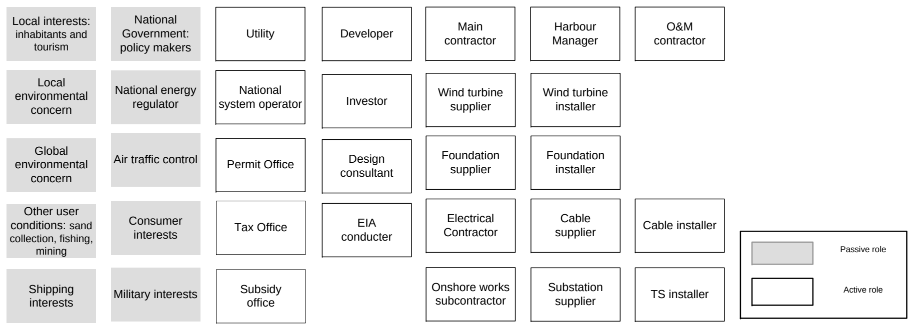


Figure 5.14: The RoleModel presenting all relevant roles, separated in passive and active roles.

made that shows the agents, their environment and the interactions between the agents. For the identification of the interactions between the agents, the simplified contracting scheme (figure 5.11) is used. In figure 5.15 the AgentModel is presented, the main result of the identification of the agents as stated in the methodology in chapter 3. The agent types are the active roles on the right side of the figure. The passive roles are a part of the Environment of the agents, on the left side of the figure.

The agent representing the role for project development (the Developer) writes out a tender for a turnkey contract to a main contractor agent (the MainContractor). For the turbine, three specific roles are identified: the turbine contracting, turbine installation and maintenance. A turbine contractor-agent (the TurbineContractor) is hired by the agent MainContractor, and the TurbineContractor makes contracts with a turbine installer-agent(TurbineInstaller) and maintenance contractor-agent(OMContractor). For the foundation, a FoundationSupplier and FoundationInstaller is hired by the MainContractor. For the electrical system, five agents are present: the ElectricalContractor makes a contract with a CableSupplier and a SubStationSupplier, who in turn hire a CableInstaller or StationInstaller respectively. The MainContractor hires one OnshoreWorksAgent for all work for the grid connection onshore.

The Developer has interaction with Investors, EIAConductors, DesignConsultants and Utilities. It also has contact with the unique agents PermitOffice, SubsidyOffice and TaxOffice. These agents are unique because there will be only one instance of this agent type in the model, while the number of agents of e.g. type Developer can be higher. The NationalSystemOperator that is in contact with the Utilities is also a unique agent.

The passive roles, represented in the Environment of the agents, represent the interests of other users (fishing, shipping, air traffic control), consumers and interest groups as identified in tables 5.12 and 5.13. Governmental policy is

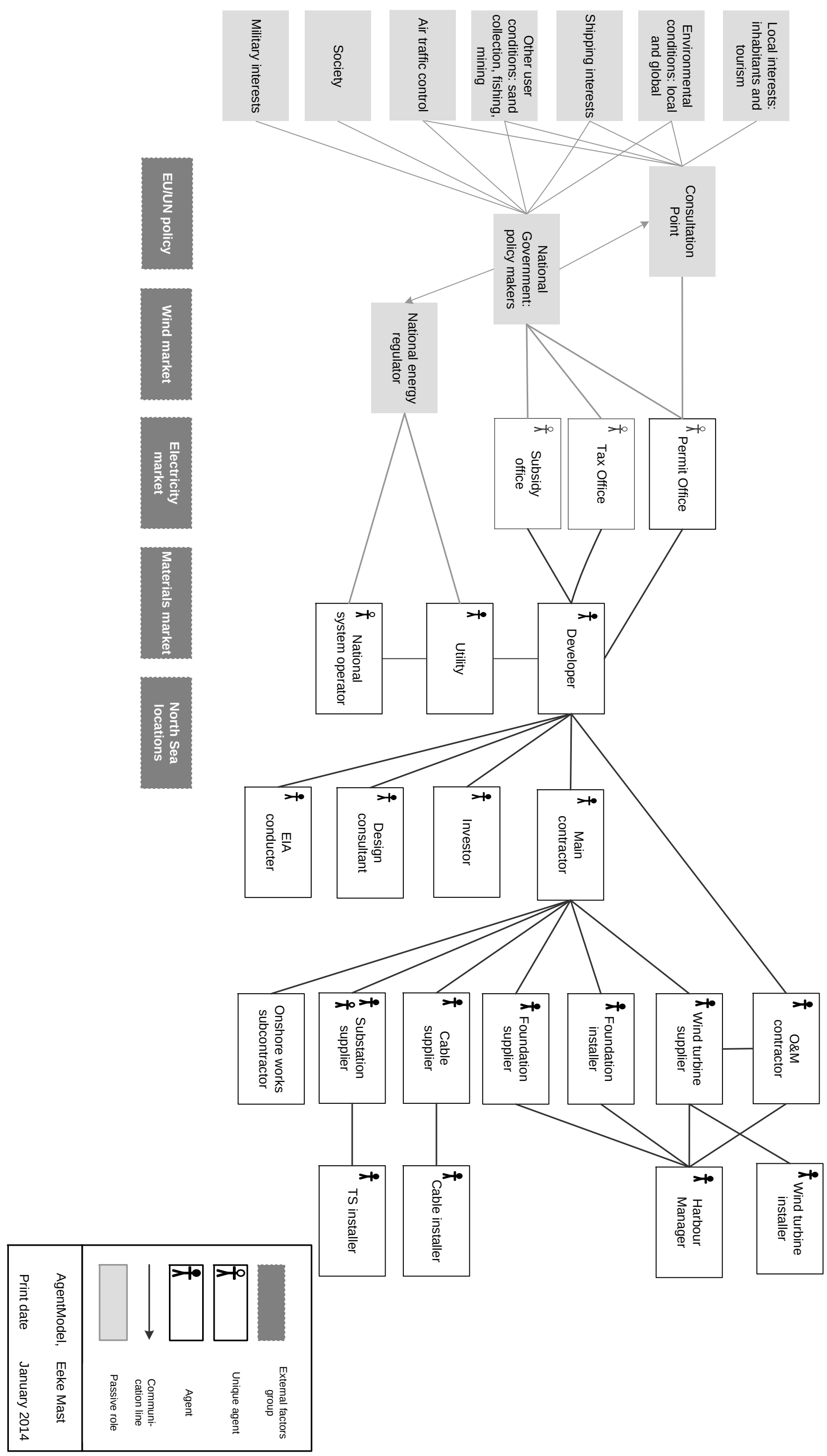


Figure 5.15: AgentModel

also a part of the environment, although the actual execution of this policy is included in agents: the SubsidyOffice, the TaxOffice and the PermitOffice. The choice of external factors are stated in the AgentModel: EU policy, the locations in the North Sea and the markets for (offshore and onshore) wind turbines, materials and electricity. This choice will be explained and detailed in chapter 7.

In developing the agents, the focus lies on certain agents consistent with the focus of the research as laid out in chapter 4. These agent types will be worked out in more detail than the other agent types. This will be discussed in the next chapter, where the behaviour of the agents is explained.

5.4 Summarising the model development

Four requirements were set for the model development. The first requirement stated the role-based approach instead of an actor-based approach. The simulation is then still based on actions of actors in real life, but they are represented by their roles in the simulation model. In this simplification of reality, a meso-level model is achievable that includes relevant perspectives to the implementation in the model, as a micro-level analysis of all identified actors is not required. This is consistent with the research question, as this focuses on the investigation of the implementation of large-scale offshore wind energy in the Netherlands, towards the 6000 MW target in 2020.

The relevant actors for the implementation are the stakeholders. The active roles are represented by agents because of the high and dynamic interaction with each other. The passive roles are condition-setting and will therefore be taken along as part of the Environment of the agents to limit the number of agents. Together, a broad range of roles is incorporated in the model and thereby a broad range of perspectives on the implementation is incorporated: requirement two is met.

In requirement three, it was stated that all major parts of a park should be included. Using cases it has been concluded that the project construction consists of contracts for five major parts; the turbines, foundations, electrical system divided in sea-cables and the substation, and the onshore work. The roles directly in contact with an actor in the role of multi-contracting are the contractors for supply or installation of a part, or both supply and installation. In the general supply chain, suppliers include design, manufacturing, transport, and commissioning while installers transport to site and install the part. Part of these activities can be subcontracted to others, but only contracting for suppliers, installers, harbour space and O&M are included in the study. These simplifications were made to reduce modelling time, following requirement four.

The resulting agents and their environment are depicted in the AgentModel, see figure 5.15. It shows the agents and their interactions and environment, using the simplified contracting scheme and the influences from the passive roles. The following chapters work out the model design in further detail. The agents' behaviour will be discussed in Chapter 6 and the environment of external factors and passive roles' attitudes is discussed in chapter 7.

6

Agents and their behaviour

Introduction

In this chapter, it will be explained how the agents have been implemented. This chapter addresses the key questions of how actors can be represented as agents in an agent-based model and how their behaviour and capabilities can be described and represented as implemented behaviour of agents. The steps taken to design these agents and their behaviour will be presented.

First, the decision making of the actors is discussed, followed by how this has been modelled as the behaviour of agents. Second, the steps in the design of the agents are discussed. This addresses how the required behaviour of the agents for the simulation is identified and transformed into the procedures and protocols that will be included in the simulation. Third, the implemented behaviour for the most important agents is described. Fourth, concluding remarks are made about the agents' implementation.

6.1 Representing actor's decision making

6.1.1 Determining the basic concepts for behaviour

The behaviour of the agents entails how the agents will make decisions and which actions they take: e.g. what information do they gather, how do they balance several options or decide to invest. Their modelled decision making has to represent the decision making of the actors. For this, first the view on the decision making of actors is described. Second the general view on decision making agents is given.

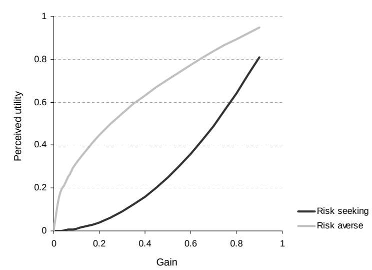


Figure 6.1: Example utility functions for the risk averse and risk seeking.

6.1.2 Actors and decision making

From a neoclassical economics' point of view, decision makers are assumed to show rational behaviour towards their aim in maximising their profit. In a perfect situation, a decision maker can see all the information and alternative actions so he can select the action that will maximise is profit. However, in previous work several authors have noted that such behaviour is in fact impossible due to limitations of the actors. The behaviour of actors is influenced by uncertainty, rationality limits and trust.

Risk and uncertainty

A decision will have a certain result, for instance the profit (or loss) incurred. This result will not always be clear in advance, but dependent on the future state of the world. A classic example is the decision to bring an umbrella on a day out: the 'pay-off' is dependent on the weather. If you bring an umbrella and it does not rain, you would regret bringing the umbrella, but if you do not take it and it rains you would regret not bringing it. Since the future state of the world is uncertain, the result of a decision is uncertain.

An actor will have a preference over the possible results of decisions: he has a certain *utility* value for the possible outcomes. The preference or utility of different results will depend on the person's risk attitude: a person is said to be *risk averse* when he would rather accept a smaller return to reduce risk, while a *risk seeking* person dares to take more risk. For a risk-averse person, this would influence his decision as he is willing to miss out on some profit in exchange for a more secure profit, while a risk seeking person is willing to risk an amount for the larger gains. In figure 6.1 two utility functions are drawn representing this: a risk-seeking person has smaller utility for small amounts and his utility function starts to rise faster when the amounts become larger, while or a risk-averse person, his utility is already higher for small amounts.

In deciding their actions, actors can have different attitudes towards risk and uncertainty, leading to different strategies for decision making. In taking an action, the actor can look at the expected profit, or at the expected utility of the results of a decision and maximise his utility. The actor can minimise his (maximum) regret, where regret can be defined as the difference between possible higher profits (or lower loss) had another decision been taken versus the realised profit or loss[1]. The actor can maximise the minimum profit. Therefore, in an uncertain world, the maximum profit that can be incurred does not have to be the only parameter; also the risk attitude influences the chosen strategy of the actor. For example, Philip Martens of SeaPower stated that the 'largest competitors of offshore wind power parties is offshore wind itself', referring to the situation that a failed park can have a huge influence on the public support for other wind farms. A very risk seeking attitude for developers would therefore not be expected, especially in the beginning stages of implementation.

Uncertainty and risk example in offshore wind parks

When choosing the criteria for an EPC tender, project developers does not look solely at price. Tender criteria will also incorporate other factors and state how they will be weighed against each other. Tender criteria often include the price, quality and after-sales agreements [26]. These elements can be given points, for instance on a scale of 0-100 and then the total sum for all elements gives a ranking, using a weighing of the elements as for example [26]:

Price	weight: 3/10	
Quality	weight: 3/10	Quality systems, references
After-sales	weight: 3/10	Service after delivery
Extra	weight: 1/10	e.g. safety and logistics systems

In such a point system-tender, it is not just the price determining the tender winner, but his experience and quality of his products can be weighed in. By taking into account more than just the price, the (technical) risk can be reduced for the principal: a risk-averse principal will have a lower weight on price and a higher weight for the quality systems and references of a tenderer (and its products). For example, a larger wind turbine can lower overall project costs, but can increase technical risk: a developer might prefer a more 'tested' machine despite the cost advantages.

Rationality

When the 'rational man' is considered to be a decision maker that fully maximises his utility, he then (still) has to have a clear view on all possible choices, the set of all possible actions denoted here as $\mathcal{A}$. He should have complete preferences over these actions, providing a full ordering of the utility of all actions in set $\mathcal{A}$, and the actor should have the computational capacity and full information on his environment to calculate these utilities. Only then will the decision maker be able to choose the action with the maximum utility [209].

[1] In reference to the example in the beginning of the section: would you regret more getting wet or redundantly carrying an umbrella?

However, the concept of an omniscient decision maker is not possible in real life. As Simon [223] pointed out, a (real) decision maker has but limited computational and knowledge capacity. He may have to decide under time restraints. He therefore may not choose the action that will maximise his profit or utility, as it is not possible to assess or even know all possible alternatives. The decision maker sees only a subset of the set of actions $\mathcal{A}$, as in reality alternatives are not given but sought [223]. Limitations of human knowledge and computation prevent the behaviour of the perfectly rational man. Instead, loosely articulated heuristics, or rules of thumb are used when gathering information and making a choice [225].

Actors should not be dismissed as irrational if they do not ‘simply’ maximise their profit or utility. In finding a profit maximising strategy, information gathering adds a cost[2] which might be higher than the extra profit to be gained. Since the costs of gathering information are, in general, unknown, one cannot say which actor is more rational: the actor that searches for the optimal solution and pays the information gathering costs for this, or the actor that chooses the first acceptable option. Simon defines the latter as ’satisficing behaviour’ [122].

An actor may not know his own utility function, but he can still act rationally. Simon introduced the term ’bounded rationality’ to describe a limited kind of rationality, as a combination of rationality and boundary conditions ([224], [122]). Here, the context of behaviour is shaped by Simon’s boundary conditions, such as limited information and processing power. One then considers rationality as bounded by these conditions. Simon considered a decision maker *‘procedurally rational’* if he makes a decision after due deliberation following certain procedures. This requires a decision maker to make the same choices in the same situations, and in that way he is a logical, rational decision maker, even though the decision might not be optimal choice.

The term bounded rationality has since been broadened by Williamson and Nelson&Winter [122]. Nelson and Winter state that because of bounded rationality, firms are not able to calculate through the options and use evolutionary theory to explain the persistence of routines in decision making that are a part of the ‘fittest firms’. These routines can be simple decision making rules as the rules of thumb mentioned by Simon.

Rationality example in OWE

In offshore wind energy, as in other sectors, there are parties with limited information on all costs. For example, there is an information asymmetry between developers and the subsidy office, as the subsidy office has only limited information on the real costs of an offshore wind park. The subsidy office may intend to support the developer with a subsidy to make the park economically viable.

[2] This is an example of a transaction cost: remember the example in section 3.1.5 on page 43.

A profit margin is expected to be desired by the developers, but the subsidy office will want to avoid windfall profits due to too much assigned subsidy. Such information asymmetry could occur if the task cannot be monitored and if the contractor has specialised knowledge.

Trust and opportunistic behaviour

Williamson [264] used the term 'bounded rationality' to describe that not everything can be known in contracting as there are limits on capabilities in dealing with information and foreseeing the future. Bounded rationality and information asymmetry can increase contracting problems, as one of the parties could show *opportunistic behaviour* to take advantage of this asymmetry. In general, opportunism may arise if the outside firm can achieve a higher profit at the expense of the principal. A good contract that includes safeguards can diminish opportunism by explicating agreements and expectations, but to drag a firm to court is not a costless effort and litigation is not fully predictable[3] [171].

Trust between two parties in contracting can decrease contracting costs and opportunism. While Williamson sets aside trust as a form of governance, as firms should operate in their own self-interest to make it on the market, Nooteboom [169] states that trustworthiness should not be neglected. Although the trustworthiness of a firm cannot be communicated due to private information, opportunistic behaviour of a firm can be estimated by looking at previous behaviour: it can be inferred from previous, observable behaviour. Trust can develop between two firms by previous interaction and learning from previous experiences, defined by Zucker (cited in [168]) as 'process-based trust'. Opportunistic behaviour decreases the possibilities for future contracts, whereas 'good behaviour' increases trust. Transaction costs can be reduced when entering in an activity for a second time, because experience has decreased information gathering costs if this had already been researched the previous time, and trusting means assuming a lower risk of opportunistic behaviour. Previous experience therefore reduces cost and can increase trust.

The issue of trust in repetition has also been a topic in repeated games in game theory. In [14], Axelrod simulated a repeated game where both players get a certain return (say 10) if they both 'cooperate', but if one 'defects' while the other 'cooperates', the one gets a higher return (15) while the other get a lower return (5). Axelrod showed that the tit-for-tat strategy performed best against all other strategies in a simulation of 2000 repeated games. In each game, this fairly simple strategy reciprocated with the same action of the adversary in the previous round.

[3]This issue is addressed in choosing the form of the firm: which activities should be integrated into the firm for protection against the risk of opportunism and hold-up versus e.g. possible reduced economy of scale of a specialised firm in one activity.

Trust example in OWE

When a contractor subcontracts an activity, he might have a preference to whom he subcontracts it to. A party he has worked with before with good results could be preferred over a 'new' party, even if the new party offers to perform the activity at slightly lower cost. Such subcontracting preferences could of course also have to do with the subcontractor being a subsidiary of the contractor.

6.1.3 Actors behaviour represented by agents

In modelling the agents the behaviour of actors has to be captured. In the previous section it was explained that actors are not seen as 'simple' profit maximisers, but their behaviour includes the use of routines, rules of thumb, issues of trust, uncertainty and utility. This behaviour will be mirrored in the behaviour of the agents. The behaviour of the agents consists of the actions of the agents and how it decides these actions. An action can be an internal action changing only its own state or an external action changing its environment or affecting other agents (e.g. by sending a message). How it decides to take action consist of three basic questions it asks itself, which lead to the actual action decision:

- What do I see?
- What can I do?
- What do I want?

The information accessible to the agent is limited, as an actor has to deal with limited information. What it sees is not the world (consisting of the environment and the agents) itself but the agent's *perception* of the world. The agent is not presumed omniscient, and it will therefore have limited information on its world. This world perception consists of the perceived environment and the other agents, as well as the perceived state of the agent itself. The agent is therefore not a perfect decision making unit, as its information can be insufficient. This does not mean it is not a rational decision maker: considering its perceived world, it may take the rational decision.

Before an agent decides what to do, it has to check what it can do and what it is permitted to do. Not all actions could be possible in each world: an agent might be affected or even restricted in which actions are allowed by *behavioural rules*[4]. These behavioural rules can represent social rules or physical rules. Physical rules denote certain restrictions arising by the nature of the part of reality depicted; e.g. the law of the conservation of mass, or a certain crane

[4](Scharpf [213] stated there are different rules in different contexts, so decision making is dependent on the perception of the world.

can only carry a maximum weight. Social rules are rules in social interactions, arising from a socio-institutional setting, e.g. one should not break a promise, and if you want to build a wind park you have to have a permit. Apart from this limited information and the limiting rules, an actor also has to deal with its limited calculation power and the costs of gathering information, leading to for instance deciding by rules of thumb instead of full optimisation procedures. Such rules of thumb will be represented in the decision making of the agents. Following notation in decision theory, all actions will be denoted by $\mathcal{A}$, and the agent's perceived world by $\mathcal{E}$. An action that can or may be taken in a certain perceived world can be noted as $\{\alpha, \mathcal{E}\}$, where $\alpha \in \mathcal{A}$. The possible actions they perceive is only a subset $\mathcal{A}'$ of the set of all possible actions $\mathcal{A}$.

All behaviour is guided by what an agent's defined objectives or *goals* are. The goals or objectives are the states that an agent wants to achieve, and the set of goals are denoted by $\mathcal{G}$. The decision of an agent can then be denoted as the tuple $\{\mathcal{E}, \mathcal{A}', \mathcal{G}\}$ [5]: the agent chooses an action leading to desired new state, based on his perceived world and perceived possible actions, guided by goals and restricted by rules.

In the limited information of the perceived world of the agents and their set of possible actions, it is intended that the agents mimic the assumed bounded rationality of the (roles of the) actors they represent. Apart from limiting their information and set of alternatives, also their calculation capabilities and search time of the agents are assumed bounded: agents can use simpler 'rule of thumb' instead of a full optimisation procedure. The agents are trustworthy in the execution of the contracts they sign but they set their profit margin as they see fit and this is dependent on private information (information asymmetry present). Previous experience with a contractor can give a preference.

It should be noted that, although the agents are considered 'boundedly rational', the agents can never be illogical [164]. Agents can be considered procedurally rational, stating a logic consistency in their behaviour. This includes for instance the requirement of transitivity in their decision making: if A is preferred over B, and B is preferred over C, then A should be preferred over C[6]. Random variables can be used to add random behaviour, however such random behaviour can make the results more difficult to interpret. Random behaviour has therefore not been included.

[5] Adapted from [193]

[6] $A \succ B$ and $B \succ C$, then $A \succ C$ should be true ($\succ$ denoting the preference relation).

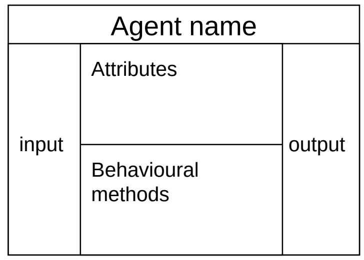


Figure 6.2: Basic form of an agent, adapted from ([164], [25])

6.2 Designing the agents

6.2.1 Basic form of an agent

All agents have to be implemented in the chosen programming language. They first have to be designed, and object-oriented modelling techniques are presented that have been used in the modelling. An agent is an instance of a certain type or *class* of agent, for instance a Developer agent[7]. A class is a type of agent that share all the same attributes and methods[8], as an abstraction of an agent type, while an instance is an object or agent as a concrete manifestation [25] of a class.

In UML [25], a class can be depicted stating its name, attributes and operations. In [164], Nikolic assumes an agent to consist of input, a state, rules and output. Its state is formed by its parameters and the behavioural rules represent how inputs and the internal state lead to outputs. Here these diagrams are merged as the basic form for an agent. The input-state-rules-output description is adapted for the initial design of agents to input-attributes-behavioural methods-output. The behaviour represents the rules but also set of possible actions and goals of the agent. This gives the diagram depicted in figure 6.2, which is used as in the design phase to collect all required input, output, attributes and methods for an agent class.

6.2.2 Steps in agent design

To fill in the basic form, the operations or methods and attributes have to be chosen for each type or 'class' of agent. This means that in designing each class, the rules, goals and world view have to be identified as the content for an agent type. This will determine what each type of agent can and will do in the simulation. The involved actors' actions, objectives, perceptions and rules form the basis for the possible actions, objectives, perceptions and rules. Therefore, to model the agents one can look at which situations of reality should be included

[7]The capital represent a class of objects, while an instance of that class would be written in small case letters: a Developer is a class, a developer is an instance of that class.

[8]In Java, the attributes of an object are its variables and its methods are the (private or public) procedures it can perform [128].

and what (inter-) actions of agents go in these situations. This leads to the goals and actions of the agents.

The above steps are the steps as mentioned in the methodology in chapter 3. In the methodology, these steps were introduced as part of the design phase as preliminary design tools. In further detail, the steps for the design phase are:

1. Make use cases,
2. Translate the use cases into interaction diagrams,
3. Make an initial design using the interaction diagrams,
4. Make a detailed design for each agent from the initial design.

In the next subsections, use cases and interaction diagrams are explained. In the next section the results of the steps are discussed per agent.

6.2.3 Use cases

For the agent-based model, adapted *use cases* have been used in the design phase. Use cases were first defined by Ivar Jacobson in software engineering as descriptions of how an external user or another system can interact with the system to achieve certain goals. A use case expresses expected behaviour from the system to be implemented, without going into how this should be implemented. In [25], a metaphor for a use case is used concerning an architect designing your house: when talking to the architect you focus on how you would like to use the house he is designing for you, without going into how the architect will implement these wishes in a detailed design.

In this case, the use case focuses more on what type of situations should be simulated in the model, not how it should interact with an external user. In Jacobson's definition the 'external actor' had a goal in a use case, here the modeller translates the functional requirements in situations agents will have to simulate. The triggering event is not an external user or system trying to achieve a goal, but the different situations the modeller wishes to explore and simulate in the model. The adapted definition of use cases for this study then becomes, in adaptation of [40]:

> A use case is a description of the possible sequence of interactions between the agents and their environment within the system, related to a particular situation the modeller wishes to simulate.

To determine which use cases (which chains of events) should be simulated, the focus as defined in chapter 4 is leading. The use case starts with a certain goal that has been set for the model, e.g. 'we wish to simulate the development of a site to an offshore wind park'.

Example of a use case

A use case will be described in the planning of a park by the DeveloperAgent, in the role of project development. The DeveloperAgent wants to invest in off-shore wind parks to receive a profit. For this, he first has to decide which site to develop. In short, the use case set-up is as follows.

> **USE CASE: PlanningPark**
> *DeveloperAgent goal:* I want to invest in a park to make a profit.'
> *Situation:* the subsidies are only given for selected areas.
>
> DeveloperAgent: 'I have to know what the relevant permit procedure is and how the arrangements are for subsidies. I have to decide whether a park is a good investment based on the estimated costs for construction and operation, my expected income for revenue and subsidy and the risk of the investment. The risk of the investment is determined by my previous experiences considering regulatory stability and revenue.'
>
> After selecting a site, a Developer agent wants to decide if this site is a good investment and if he should continue planning the park for this site. To estimate the costs and risks, he needs information from the Environment and contractors on expected costs and timing for construction and delivery. The contractors select what information they want to send to the Developer agent. The DeveloperAgent receives the status for the permits and subsides from the PermitOffice and the SubsidyOffice. He considers the probability of receiving the permit and a subsidy. The estimated utility of the sites reflects the likeliness of subsidy or permit for the site. The Developer agent makes a preliminary design and estimates the costs, income and risks and chooses to invest, not to invest or to wait.

6.2.4 Interaction diagrams

The use cases can be translated into interactions between the agents. A useful tool to sort and represent the sequence of interactions is an interaction diagram. It is used as a standard method in object-oriented programming as well as in several AO methodologies, such as Prometheus and GAIA ([191], [272]). An interaction diagram also gives insight into which methods agents will need for its decision making and interaction. Not all use cases need to be translated into interaction diagrams: some use cases may describe a desired functionality that entails limited interaction between agents. The interaction diagrams can be found in Appendix D.

The basic shape of an interaction diagram is shown in figure 6.3. In each of the top boxes one sees the name of an agent class, and from each box a vertical line downwards represents the time line, with time running from top to bottom.

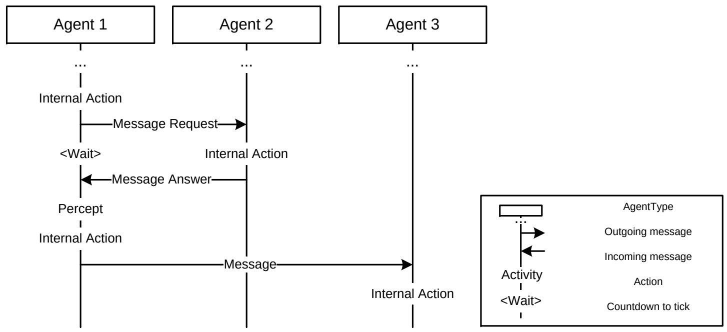


Figure 6.3: An interaction diagram.

On the line the sequence of actions are shown. Messages to another agent are represented by an arrow going from the vertical line of the initiating agent to the line of the receiving agent. A notation on the line from an agent box represents either an action of the agent or a *percept*, a received message from the external environment [191]. In this way, the interaction diagram shows the sequence of actions and interactions. Alternatives in sequence can be depicted by a dashed box and a condition in the upper right corner[9].

To communicate, agents have to be able to send each other messages. The response is given by the addressed agent directly, or the addressed agent responds later, in his allotted time slot. For the latter case, messages are collected in action lists. For example, a developer can send a message for a permit request to the PermitOffice, which ends up in the list *requests*. The PermitOffice goes through this list in its time slot at his own pace, depending on the permit procedure in place.

Example of an interaction diagram

In the model, the Developer agent writes out a tender to represent the turnkey contracting for the project. This is represented in the interaction diagram in figure 6.4.

The agent of the Developer type places a tender invitation in the World, which can be read by everyone. The tender invitation includes the selection criteria. Main contractors look for tender invitations of this type and see if they fit the selection criteria and if they would like to participate (considering their work load and the location of the project). If they decide to participate, they send a message to the Developer with the necessary information. The Developer agent selects a number of MainContractor agents that satisfy the selection criteria for the tender and sends them a message with the tender criteria. Such tender

[9]Related to the illustration of protocols as described in [192].

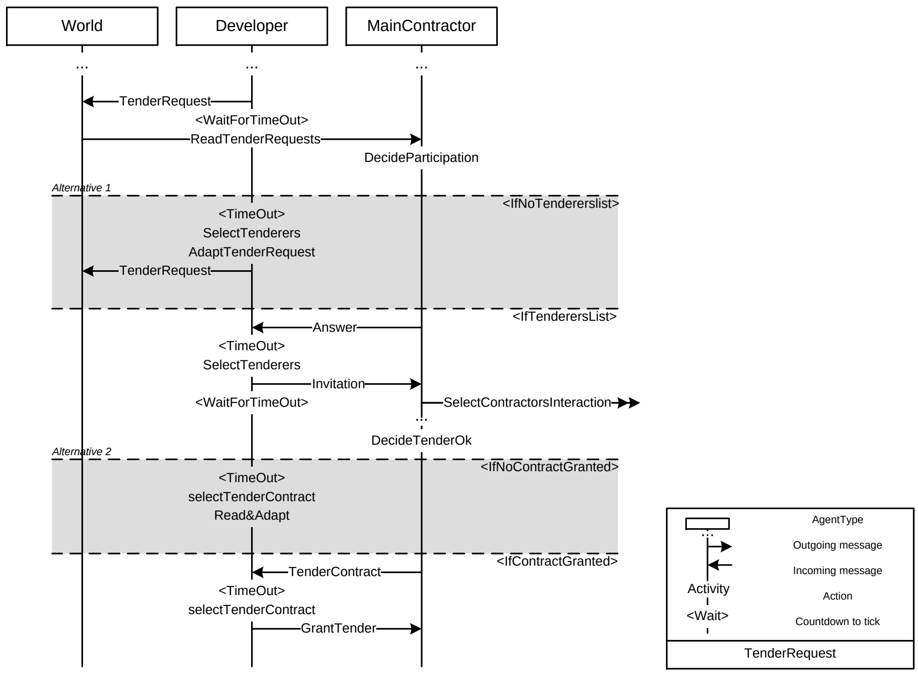


Figure 6.4: The interaction diagram 'TenderRequest'.

criteria can include basic design parameters (e.g. the preferred size of the wind turbine). The Developer agent then waits for a predetermined time until the tender has expired. Meanwhile, the MainContractor agents invited to tender try to make contracts with the subcontractors and, when successful, respond. The Developer agent then goes through the responses and selects the tenderOffer it wishes to accept and sends a message to the chosen MainContractor agent to go to the financial close.

6.3 Results of agent design

6.3.1 Focus on a selection of agents

This section shortly describes the results of the design phase. The agentModel was presented in chapter 5 and depicted all the agents in the simulation model. In chapter 4, the focus of the research was determined on the following topics: permit procedures, financial support, layout and timing of an offshore grid, the availability of resources, specifically the wind turbines, and the innovation of the wind turbines. This focus in topics leads to an emphasis on certain agents. Certain agents will therefore be more elaborate in their implementation and will therefore be more complex than other agents.

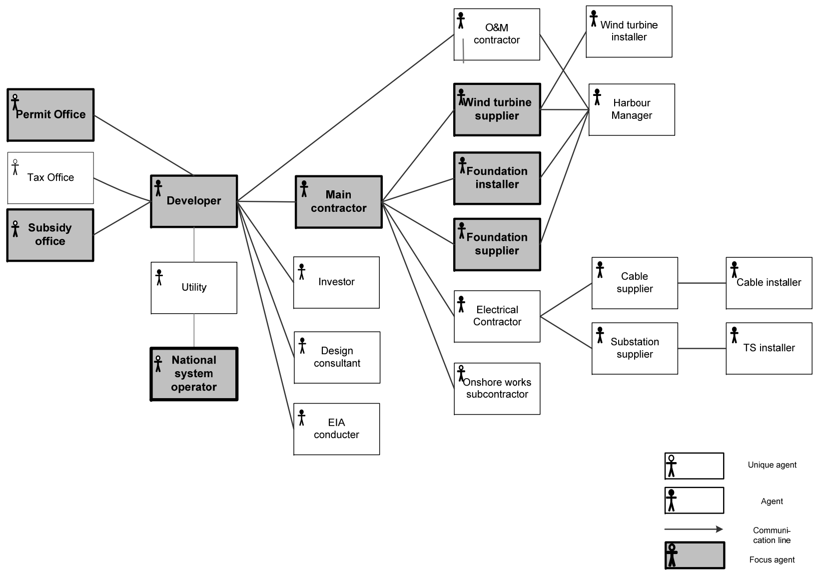


Figure 6.5: In the AgentModel the agents that are darkened will be implemented with more elaborate and complex behaviour.

The agents that will be more elaborate in their implementation are depicted in figure 6.5 as the grey-coloured agents. The NationalSystemOperator is chosen for the planning of the offshore grid. For the emphasis in the wind turbine supply and characteristics, the TurbineSupplier agent will be more detailed. The PermitOffice and SubsidyOffice will receive more attention in the implementation to incorporate different procedures for the permit and financial support. The focus on these procedures also dictate an emphasis on the Developer agent class. For an overview of the required resources and timing, the MainContractor will be one of the focus agents, as well as the FoundationSupplier and FoundationInstaller as they are involved in the costliest main part after the wind turbines. For these agents, a description will be given of their main attributes, their decision making rules and the information they can share or receive. The agents representing the roles of market parties all have a similar basic goal: to earn a profit and reduce risk. The basic goal of the other agents (the PermitOffice, SubsidyOffice and GridOperator) are to perform the tasks assigned to them by the government.

6.3.2 The Developer agent

In section 5.2.2 the six phases of realising an offshore wind park were described: the planning phase, the procurement phase, the construction phase, operation and maintenance (O&M) phase, re-powering phase and the decommissioning phase. These phases can be recognised in the main activities of the developer,

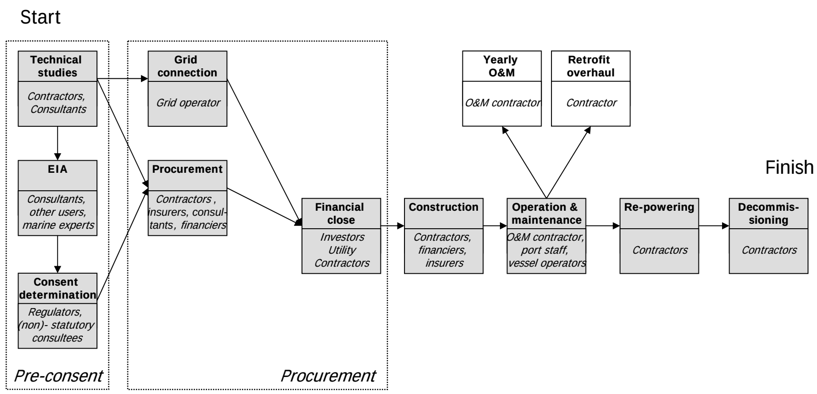


Figure 6.6: The activities in the realisation of a park from the perspective of the project developer (adaptation of Annex B of [97]).

identified in figure 6.6 in a project path. The activities in the pre-consent phase and the procurement phase are the most complex for a Developer agent, and these will therefore receive extra attention.

The use cases PlanningPark, PermitRequest and TenderRequest have been made to describe the activities in the pre-consent and procurement phase, e.g. performing technical studies, ordering the Environmental Impact Assessment, and applying for consent. All three have been detailed in interaction diagrams, which can be found in Appendix D. The use cases and interaction diagrams lead to a basic sequence of actions of a DeveloperAgent for a park, depicted in figure 6.7. The figure shows a schematised view of the steps and decisions in one park. This sequence is not worked through in one time step, as the time duration of the activities needs to be portrayed. In each time step, the Developer agent continues where he left off with the park. The Developer agent has rules governing how many parks in total it can take on in each phase. The activities of site selection, initiative decision and tender publication (selectSite, the decisionInititative and the publishTender in figure 6.7) will be discussed here in more detail.

Selecting a site

The environment contains a set of North Sea Locations representing site locations, which will be described in the next chapter (chapter 7). To make a calculated investment decision on whether or not to invest in a park at a location, the Developer needs to make a park design. However, the Developer agent is assumed not to invest his time (and money) in a park design for all possible sites in the North Sea within the Dutch EEZ. Therefore he first has to select the sites he wishes to explore. The Developer agent first makes an ordered list of the locations he wishes to explore. The ordering of this list is based on his estimated

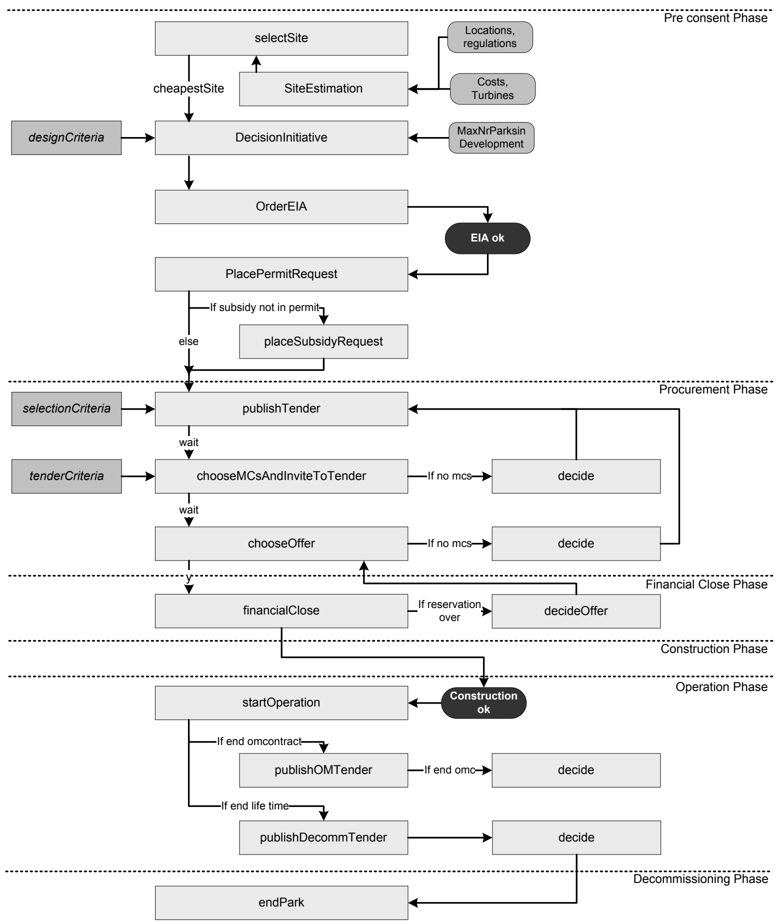


Figure 6.7: The sequence of actions for the DeveloperAgent to realise a park. At the beginning of each phase a DeveloperAgent can decide to put the park on hold or cancel it.

cost of the site and the risk of not receiving permit consent for this site. If a site is occupied by another park (with at least a permit for the site) or a permit was refused for this site before, the site is disregarded. Also, the site should be large enough for at least the minimum total installed power the Developer wishes for his park at that time. From the sites satisfying these conditions, the site with the lowest estimated cost and risk combination is found as follows:

$$InitialCost = \frac{(C_{park} + C_{grid} + C_{se} \cdot r)}{P_{id}}, \tag{6.1}$$

where C_{park} is the estimated park costs including installation, material and O&M, C_{grid} is the estimated costs for the grid connection C_{se} is the estimated site exploration cost, r represents a risk factor and P_{id} is the initial design choice for the total installed capacity of the wind farm[10]. The park and grid costs are estimated by asking other agents for a rough estimation of costs, e.g. an initial price per length from the CableContractors. The risk factor r is based on the risk of spending the site exploration cost and is determined by the number of failures and successes of the Developer's previous permit and subsidy request attempts. If a previous park failed, the risk factor will go up, representing that the Developer becomes more risk averse, while a successful park can lower the risk. The initial choice for installed capacity P_{id} is the smaller of the Developers' preferred size and possible installed capacity, where the latter is the maximum for allowed power density times the area. The C_{grid} consisting of the export cable and possibly the offshore station and onshore connection cost. When estimating the grid costs, the Developer also checks for a possible offshore connection station.

This estimation is a rough estimate to weigh the costs and risks and to order the possible parks. The resulting 'cheapest option' might not be the cheapest one when a full design of a possible park at the site is made, but due to limited time and information (due to the bounded rationality of a project developer) the Developer uses this rough estimate.

Initial investment decision and tender publication

When the most favourable site is selected, the Developer agent makes a design for the site, to determine a maximum installed power and preferred wind turbine size. The Developer agent uses the coordinates and the water depth to estimate the costs of the designed park. The Developer agent uses the X and Y coordinates to calculate the distances to the harbour and the nearest high

[10] Although estimating Cost of Energy might have been a better choice, the model as it is does not differentiate O&M costs per park and the power output is not based on the mean wind speed. When a wind speed probability distribution and power curve is assumed, a wind speed-dependent power output can be estimated. For the sites, the mean wind speeds vary from 9.7 to 10.4 m/s, and the latter would give about 7% more annual energy output, but this has not been taken into account.

voltage station using the Haversine formula. For the calculation of the distance to an onshore high voltage station, the distance to the coast is calculated as the shortest distance to a linearised coastline. The Developer agent uses an estimation of his expected profit and cost to determine if he wants to continue with the development of this site, meaning the permit request and procurement for the park. The investment decision is made if the Net Present Value (NPV) estimate is positive. This estimate is constructed as follows:

$$cost = C_{site} + C_{dev} \tag{6.2}$$

$$income = (p_{ppa} + p_{sub}) \cdot P \cdot cf \cdot 8766 - C_{om} \tag{6.3}$$

$$NPV = -\frac{cost/2}{(1+r)^0} - \frac{cost/2}{(1+r)^2} + \sum_{i=3}^{Y+2} \frac{income}{(1+r)^i}, \tag{6.4}$$

where *cost* is the estimated costs, C_{site} is the estimated cost for the park, C_{dev} is the estimated development costs, and *income* is the total estimated yearly income. In the estimated income, p_{ppa} is the estimated price per the generated power output from the PPA , p_{sub} is the expected subsidy per generated power output, cf is the capacity factor, 8766 is the average number of hours in a year and C_{om} is the estimated yearly O&M cost. The NPV is estimated by the discounted costs for half of the park construction cost at the start of construction, the other half after construction and the estimated yearly discounted income during a set payback time Y. The payback time is assumed to be 8 or 10 years, depending on the risk attitude of the Developer. The PPA and subsidy amounts depend on the chosen environmental scenario of the run.

If the Developer decides to continue with the development of the park based on the NPV, the following activities depend on the permit procedure in place. If he first needs to obtain a permit, the Developer will request an EIA from the EIAConsultant agent. This represent the first large expenditure to the project by the DeveloperAgent. When the EIA is finished, the DeveloperAgent requests a permit. If the Developer first needs to tender for a subsidy, the EIA and permit are not requested until the subsidy is secure. When both the permit and subsidy are secured, the agent makes the decision when he wishes this park to be online. The tendering starts for the park, first by the publication of the upcoming tender with the selection criteria followed by the tender invitation to the selected MainContractors. When the DeveloperAgent receives at least one tender offer that is acceptable following the tender criteria, he will try to close the contract with the minimal costs. After successful tendering and financial close, the chosen MainContractor will start the construction. The DeveloperAgent continues with the park when he receives word from the MainContractor that the Park construction is finished.

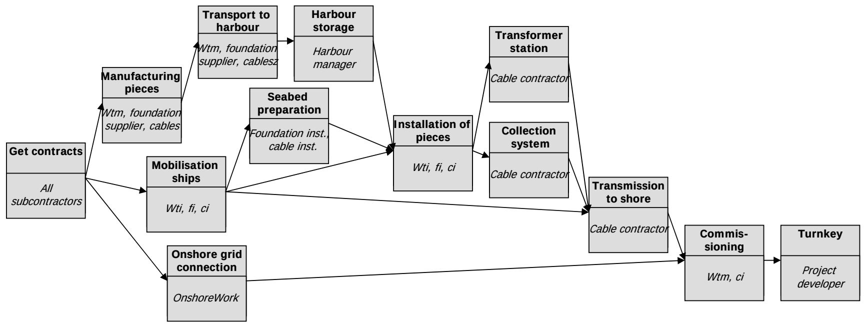


Figure 6.8: Project path of the main activities for the main contractor.

6.3.3 MainContractorAgent

The MainContractorAgent (MCA) has the task to tender to the subcontractors for the different parts of the turnkey tendercontract. For this task, use cases have been made and translated into the interaction diagrams TenderRequest and ContractorsInteraction, see appendix D. The MCA will not respond to all invitations to tenders for turnkey projects. It is limited to a maximum number of projects it can handle or wishes to handle at one time. Before the MCA can answer to the invitation to tender with its tender offer, it requests information from the subcontractors to see if the MCA can make a tender offer that meets the tender criteria. One of the tender criteria set by the DeveloperAgent is the desired end time, the time when the construction of the park should be finished. The MCA will have to find out if the subcontractors have enough resource capacity to meet this project end time. It will therefore have to plan when the different parts have to be delivered or installed.

In figure 6.8 the project path of the activities during construction of the park are depicted from the perspective of the MCA. The project path is derived from project schedules of existing parks ([186], [247]). Certain events have to be completed before certain other events can begin, while certain events can run (partly) in parallel. The timing of the activities in the project plan need to be aligned to assure the project is finished at the end time, while accounting for some delay due to waiting on weather.

In requesting offers from the TurbineSupplier, the HarbourManager, FoundationSupplier, ElectricalContractor and OnshoreWorkContractor, the MCA works back from the end time stated in the Tender to get the time for the supply and installation of the different parts. As a schedule, a simplified version of the project plan is used; in figure 6.9 this simplified schedule is depicted graphically. For each subcontract that the MCA tenders for, he sets a fitting end time as deducted from the end time of the turnkey contract tender[11]. The subcontrac-

[11] A later found error has been made in implementing this: unfortunately the foundation-

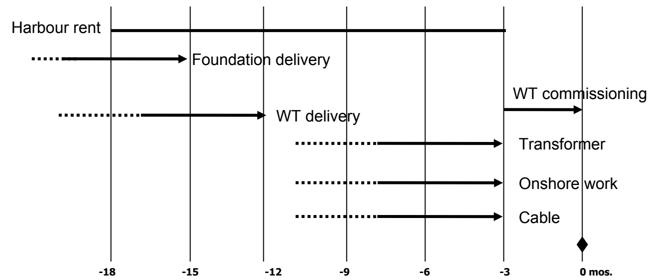


Figure 6.9: Runtimes for an offshore wind farm used in the model. Based on the time to finish for the park, the main contractor determines end times for the various parts of the park.

tors can then check in the agenda of their resource(s) if they can deliver/install in time. For each selected subcontract, reservations in the subcontractors' Resource Agenda's are made. When checking availability, the subcontractors take into account whether previous reservations are made for the same park. Upon receiving (losing) the tender, the MCA fixes (cancels) all the contracts with the subcontractors.

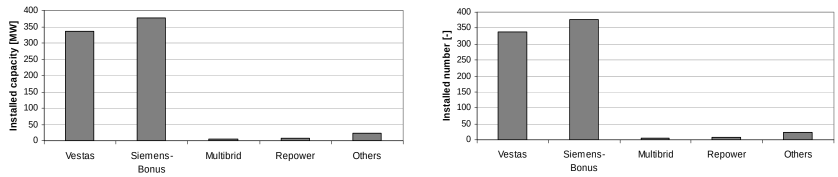
6.3.4 WindTurbineSupplier agent

The WindTurbineSupplier agent (WTS) interacts with the Developer agent, the WindTurbineInstaller agent, the HarbourManager agent, the O&MContractor agent and the MainContractor agent. The WTS gives basic information to the Developer on wind turbine pricing during the pre-consent phase. The WTS offers the MCA possible contracts for supply and installation of wind turbines, including the price, available turbine sizes (MW) and capacity factors of the wind turbines, during the procurement phase of a park. These interactions are described in the interaction diagrams ContractorsInteraction and PlanningPark in appendix D. The WTS has as its main Resource types the Turbine and the TurbineFactory.

The Turbine

The Turbine has as attributes a generator size with rated power in MW, an experience level and a capacity factor. The experience level represents the time the wind turbine has been in commercial production. The WTS determines to invest in a new turbine of the type Turbine depending on the rated power of its last wind turbine and a base size development for the applied scenario. The base size development is input from the environment. It represents the general development of the size of wind turbines. This input will be represented in the

Delivery has been set at the start of commissioning instead of the start of the harbourLease. For the booking Agenda this has no impact, except a timeshift versus the Agenda's of other Resources.



(a) Installed capacity (b) Installed number

Figure 6.10: Total capacity and number of installed turbines per manufacturer up to 2009. (Data taken from [12], [201])

model as either a low, medium or high development of wind turbine individual installed capacity, see chapter 7.

The TurbineFactory

The TurbineFactory has a capacity of the number of turbines it can produce during one time step[12] and this capacity is determined by an initial capacity of the Factory and the growth per year. The capacity and occupancy of the Factory of the WTS are stored in the Agenda of the Factory. The initial capacity is determined by looking at installed numbers of offshore wind turbines up to 2009.

There are several (offshore) wind turbine manufacturers, which are predominantly Danish and German companies. The installed number of offshore turbines and their total capacity per manufacturer are set in figures 6.10(a) and 6.10(b). One can see that Vestas and Siemens-Bonus have the largest market share by far up to 2009[13]: there is a considerable difference between these two and the rest. Figure 6.11 shows the number of Vestas en Siemens-Bonus turbines installed per year from 2000 to 2009[14]. To compare the numbers with the onshore market: in 2007 Vestas was the largest manufacturer of wind turbines with in total 4503 MW installed and Siemens was the sixth largest manufacturer of wind turbines installing 1397 MW [30]. In total 22.181 MW was installed, of which 200 MW was installed offshore and turbines of at least 2.5 MW had a market share of 5.3 % [30].

When the demand for onshore wind turbines is high, and the risk for the offshore market is high, turbine suppliers might be less eager for a large market share in the sale of offshore turbines. For the model, the capacity of the factory will be assigned in part to the making of offshore turbines, based on the agents'

[12] The time step used in the simulation is one month.

[13] Up to 2012 Siemens and Vestas are still the market leaders. Areva Multibird and Repower are growing and some Chinese brands (e.g. Goldwind, Sinovel) are popular in the growing Chinese market.

[14] Bonus was bought by Siemens and the Bonus turbines have been added to the graph to show the previous experience.

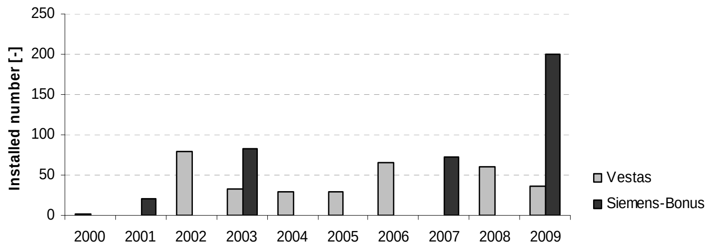


Figure 6.11: Installed number of turbines per year for Vestas and Siemens-Bonus. (Data taken from [12], [201])

confidence in the offshore market; and the share of this offshore capacity available for the Dutch market. Non-Dutch offshore wind farm development has not been included in the model, but a share of the installed offshore capacity should be assumed to be taken by orders for these farms. The chosen initial values for Factory capacity for the Netherlands is 90 or 135 wind turbines per year.

The growth of its Factory capacity will be determined by the agent's predetermined planned growth dependent on its risk attitude and the realised growth the agent reads from its Environment. The capacity available for the Netherlands depends on the capacity already available last year and the extra capacity the agents would have required to meet all requests from the MCA's. This represents the relative success of the Dutch market. To calculate the extra required capacity, the WTS remembers all requests it turned down and their requested wind turbine numbers. The WTS agent takes into account requests for the same locations in calculating this required extra capacity, as several MCA's could be tendering for the same location.

Contract offers

The WTS can offer a contract to the MCA for wind turbine supply and installation in response to a request from the MainContractor. This contract also includes the first five years of Operation and Maintenaince (O&M), subcontracted to the OMContractor. The WTS subcontracts the installation to the TurbineInstallation agent. The WTS also reserves space at a harbour with the HarbourManager, although at this time no costs are attached to this subcontract.

The WTS checks the agenda of his Factory for the delivery time of the wind turbines, which should be on or before the end time given by the MainContractor. If the Factory capacity is available, and it can make subcontracts with the OMContractor, HarbourManager and TurbineInstallation agent, the WTS makes an offer stating the total price, Turbine type and number of turbines in its offer. The price is set according to a desired profit margin, the wind turbine cost and the cost of the subcontracts. The complete pricing function for WTS is stated as:

$$price = C_{wtc,t} \cdot pm + C_{ic} + C_{omc}, \tag{6.5}$$

$$C_{wtc,t} = p_{base,t} \cdot P_r \cdot n \cdot spf, \tag{6.6}$$

where $C_{wtc,t}$ represents the cost of the wind turbine supply contract at time t, pm represents the profit margin, C_{ic} represents the cost of the installation subcontract and C_{omc} represents the cost of the five-year O&M subcontract. For the calculation of the price of the wind turbine supply contract, $p_{base,t}$ is the base price at time t, P_r is the rated power of the individual wind turbine offered, nr is the number of wind turbines offered and spf is a steel price factor varying from -10% to +10% dependent on the steel price. The latter represents the effect of the steel price on the structure. The base cost development represents cost reductions per MW due to learning and will be considered input from the environment. This base price is defined as a high, medium or low price and will be discussed in chapter 7. The desired profit margin is based on the risk attitude of the WTS; a more risk averse WTS will have a higher desired profit margin.

6.3.5 The PermitOffice and SubsidyOffice

The unique agents PermitOffice and SubsidyOffice are described here together since their actions are linked. Their actions and the sequence of these actions are dependent on which procedures are in place in the environmental scenario of the simulation run.

Three different procedures are included in the model for permits and subsidies. The first is based on the Dutch situation before 2010, where the subsidy scheme was an open ended scheme and the permit procedure was first come-first served. The second is based on the Dutch subsidy tender system as written out for May 2010, where all applicants for the subsidy tender had to have a permit for a site. The third is based on the tender system in place in the UK, which gives the tender winners a subsidy for their requested site but the permit still has to be requested. The second and third option therefore both have a subsidy tender scheme, but in the second option the permit approval comes before the tender, while in the third option the permit request (and subsequent possible approval) comes after the subsidy tender. The different options are depicted in the PermitRequest interaction diagram, depicting the sequence of permit and subsidy requesting by the DeveloperAgent (see appendix D).

Apart from this sequence of actions, each scheme is defined by certain parameters. The values for these parameters is dependent on input from the Environment representing government policy. The parameters of importance become the attributes of the PermitOffice and SubsidyOffice:

- the maximum amount of subsidy per year;
- frequency of tenders.
- maximum size (in km^2);
- runtimes of procedures;
- maximum delay time until construction should start;
- maximum number of parks constructed in one year;

If the Developer exceeds the maximum delay time, the PermitOffice can revoke its permit. The maximum number of parks that can be constructed per year represents the allowed disturbance by the construction of offshore wind farms in one building season. In the first come-first serve procedure the subsidy is set at 0.097 €/kWh following the previous MEP subsidy scheme where the fixed subsidy amount was set to 0.097 €/kWh[15]. For the tender procedure, the maximum subsidy amount is 0.15 €/kWh. It should be noted that in the 2011 energy subsidy scheme SDE+ for 2011, offshore wind is not included as it is deemed more expensive than the maximum subsidy of 0.15 €/kwh[16].

6.3.6 Grid operator and Utilities

The GridOperator agent actions represent the tasks of the TSO in the model and are described in the interaction diagram GridPlanning in Appendix D. Two of its responsibilities are dealing with requests for connection to high voltage stations and the planning of the offshore grid. For the connection to high voltage stations, the GridOperator agent keeps tab of the total capacity of the high voltage station and the connected capacity to this high voltage station. For the planning of the offshore grid it also has to plan the location and timing of realising a new high voltage station offshore. For the decision which offshore station should be realised and when, the agent receives a sequence of the locations and a time schedule as input from the current environmental scenario, although low utilisation of the previously realised offshore station can make him delay the scheduled time of construction of the next.

The locations for the onshore stations are *Beverwijk*, *Maasvlakte*, *Eemshaven* and *Borssele*, following the current available hookup points to the transport grid, and a possible new fifth station *Westerlee* [238]. For the offshore high voltage stations, the locations mentioned in the study 'Net op Zee' [182] are used. In figure 6.12 the locations are drawn in the model map of the Netherlands.

The other two responsibilities of the GridOperator are to set obligations for renewable generation in the portfolios of Utilities and to set priority access, following governmental policy defined in the Environment. If portfolio obligations

[15] Prices set at 2009 level.

[16] In the SDE+, in one year several subsidy rounds are arranged with an increasing subsidy amount for each subsequent round. The maximum amount mentioned here is the amount of the last round.

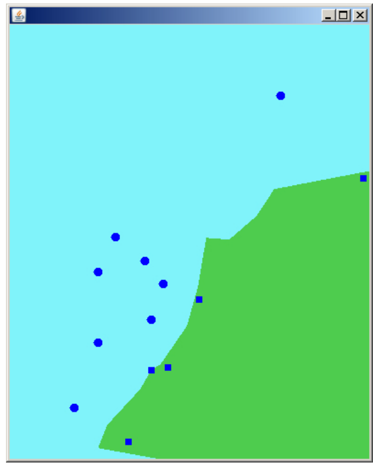


Figure 6.12: Map of the Netherlands as used in the model. The rectangles represent the locations of the five onshore high-voltage stations used for the simulations, while the circles represent the eight possible offshore locations.

are in place, the Utility agent checks if it meets this obligation and adjusts his price in a Power Purchase Agreement (PPA) offer after the request by a Developer agent accordingly. The price for electricity as offered in a PPA to the developer is set as follows:

$$price = f_{pf} \cdot f_{pr} \cdot f_{wp} \cdot f_{ubc} \cdot f_{pro} \cdot p_{el,t}, \tag{6.7}$$

where f_{pf} is the adjustment factor for the price due to possible portfolio obligations, f_{pr} is the adjustment due to possible priority access for wind power, f_{wp} is the adjustment of the electricity price for wind power set at 0.667, f_{ubc} are the unbalance costs set at 0.93, f_{pro} are the profile costs of wind power set at 1.0 and $p_{el,t}$ is the electricity price at the current time. The terms f_{wp}, f_{ubc} and f_{pro} are set according to mentioned values in [145]. If priority access is set, the price for a PPA is assumed to rise 10%. The required renewable portfolio share is set by the Environment. The f_{pf} adjustment factor depends on the risk attitude of the agents and whether the Utility meets the portfolio obligation with the power output represented by the PPA's it has already made.

6.3.7 The FoundationSupplier agent

The FoundationSupplier agent (FSA) has as its main resource its 'Factory' for the manufacturing of objects of type 'Foundation'. In the model, the FoundationSupplierAgent (FSA) closes a contract with the MainContractor for the supply (design, manufacturing and delivery) of the Foundations. The MainContractor sends the main characteristics of the planned park. The FSA sends back its price based on these park characteristics. Its Factory capacity denotes the capacity of the number of Foundations he can supply per month[17]. Here the price setting of that contract, the most important method of the FSA, is presented.

Price estimation

The price of a foundation depends on the type of foundation required for the site and turbine: mainly the foundation choice depends on the wind turbine size, water depth and soil conditions [214]. There are four basic options for foundations used today in the offshore wind energy sector: the Gravity Based Structure (GBS), the tripod or tripile, a jacket structure and the monopile.

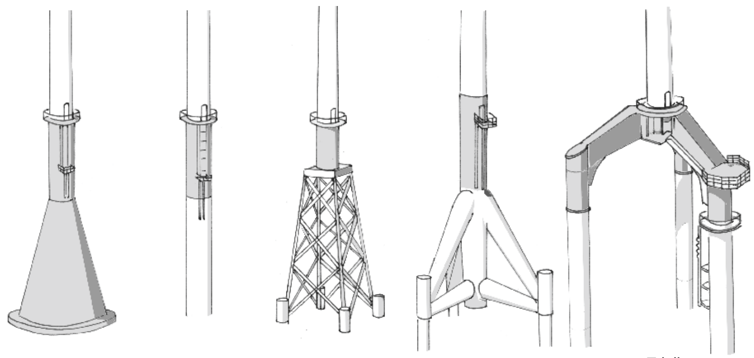
The GBS is a concrete caisson, floated offshore and filled at the site with ballast material, e.g. sand. It is kept in place simply by its weight. It uses less steel (an advantage in times of high steel prices) and it does not have to be driven or drilled into the ground. Its application is dependent on the water depth and the sea bed: they are best suited in shallow waters with a stable seabed. Jacket structures are constructed of welded tubular steel pipes and can be used in medium to deep waters up to 50 m ([72], [185]) and possibly even up to 70 m [257]. The monopile is a tubular steel tube drilled or driven into the seabed to a depth of about 30 metres. Usually a transition piece is grouted to the monopile, giving the possibility of correcting slight drilling or driving slant-errors of the monopile when connecting the tower to the foundation. Research states that monopiles can be used up to about 30 - 35 metres [232]. The tripod is connected by the seabed by three smaller steel tubes and is therefore easier for mass production [20]. Tripods can be used to up to 50 m water depth [232]. Over 50 m floating foundations come into play. In figure 6.13 a short overview is given.

In figure 6.14, one can see the water depths of the Netherlands combined with the locations of the search and preference areas of the 'Nationaal Waterplan' [152]. In the search and preference areas the water depths run from 15 to about 35 metres. The most frequently used foundation for offshore wind parks in the North Sea is the monopile. The deepest waters sofar for the application of the monopile is the offshore wind park 'Greater Gabbard', a site with water depths up to 37 m. As for water depth, monopiles could therefore be an option for all sites. Other concepts have been used for similar water depths, e.g. in Germany, the pilot park Alpha Ventus commissioned in 2009 contains containing twelve 5MW wind turbines[18] at an average water depth of about 30 metres on two different foundations: a tripod for the Multibrid and a jacket structure for the Repower machine respectively[19]. However, more experience

[17]The capacity of foundation supply is limited by the number of steel plates the supplier is able to roll and therefore how many foundations he can deliver at what time. Transport to the harbour is considered as available. In reality, these are usually barges that can carry about three foundations at a time.

[18]Six Multibrid turbines and six Repower turbines

[19]The type of foundation was chosen by the turbine manufacturers themselves [248]



Foundation	GBS	Monopile	Jacket	Tripod	Tripile
Estimated maximum water depth	< 25 m	< 40 m	< 50-70 m	< 50 m	< 50 m
Deepest water depth realised up to 2010	Thornton (B) 27 m	Greater Gabbard (UK) 37 m	Beatrice 50m	Alpha Ventus (D) 27 m	BARD offshore 1 (D) 35 m

Figure 6.13: Short overview of foundation types and the water depths for their application. *Latter three drawn after pictures from [248] and [20].*

with monopiles and the simpler manufacturing process could give this type of foundation an advantage. For this study, it has been assumed that the monopile is the preferred option. Although heavier nacelles can require a different foundation than a monopile, e.g. the tripod or jacket, due to the top mass[20], this is not taken into account here. The foundation choice is limited to the monopile.

Although data on the (future) cost of foundations are not available, estimations can be made to show a cost comparison between sites. The price of a monopile is mostly determined by the price of steel, as steel is the main material used for a monopile. The price of steel was around 1.5 euro/kg in the beginning of 2007. About 70 % of the price of a bare monopile is determined by its weight in steel ([157], [222]), the rest is the production cost as the steel plates have to be rolled and formed into tubes. The transition piece connecting the tower and the monopile is a steel tube like the monopile but connected to it is the so called 'secondary steel': e.g. a platform and a ladder. This transition piece is also processed after production, e.g. with a protective coating to protect it against corrosion. The processing of the tube and the secondary steel and transport adds another cost. About 60% of the contract is determined by the price of the primary structures, the bare piles. Using these rules of thumb from the industry, about 40% of the price of the foundation is determined by the price of the used steel. Since the steel prices vary greatly, the effect of varying steel prices will be included in the model for the foundation price. It has been assumed that while the price of steel rises, the price for processing and production does not: this remains dependent on the mass of the foundation. The price of the foundation

[20] Also, as the turbines get larger and the nacelle gets heavier, the required thickness or diameter of the monopile steel tube might reach the maximum of the existing steel rollers.

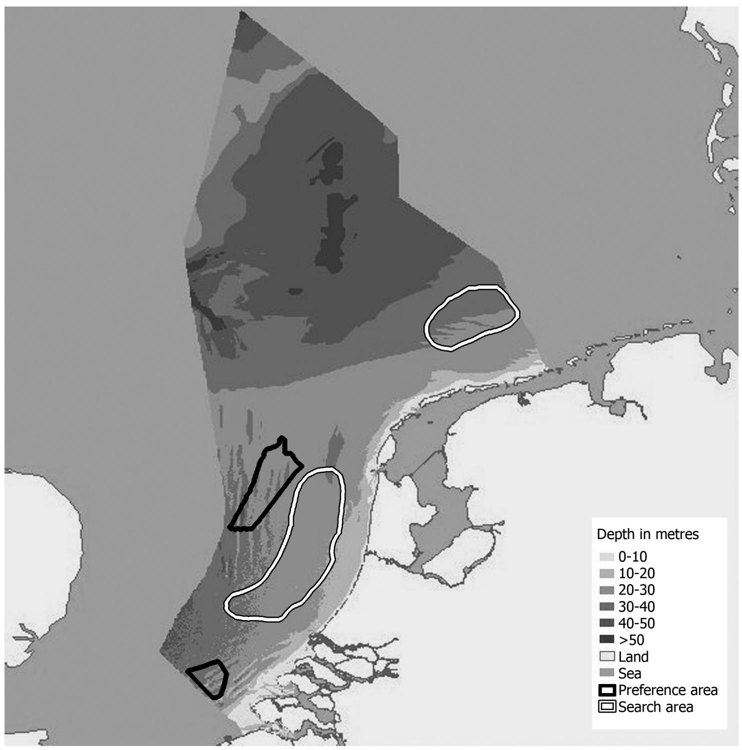


Figure 6.14: Water depths in the Dutch North Sea (*Adapted from [166], [152]*).

can then be estimated using:

$$C_{tot,t} = C_{st,t} + C_{rest} \tag{6.8}$$
$$= sp_t \cdot (W_{mp} + W_{tp}) + C_{rest} \tag{6.9}$$
$$C_{rest} = C_{tot,0} - C_{st,0} \tag{6.10}$$
$$= \frac{1}{r_{bp}} \cdot \frac{1}{r_{spr}} \cdot C_{st,0} - C_{st,0} \tag{6.11}$$
$$= (\frac{1}{r_{bp} \cdot r_{spr}} - 1) \cdot sp_0 \cdot (W_{mp} + W_{tp}), \tag{6.12}$$

where $C_{tot,t}$ is the total foundation cost at time t, $C_{st,t}$ is the cost of the steel in the contract, C_{rest} is the added cost for manufacturing and processing, sp_t is the price of steel per tonne at time t in [€/tonnes], W_{mp} is the weight of the monopile and W_{tp} is the weight of the transition piece, both in [tonnes]. At time 0, the ratio of the production cost in the total contract is r_{bp} and the ratio of the costs of the bare piles in the production costs are r_{spr}. Therefore with varying steel price the costs of the foundation can be calculated using the steel price and the weights of the monopile and transition piece.

Mass estimation

To estimate the mass of the required monopile, an existing model of Zaaijer has been used [274]. The model includes a limited number of load cases e.g. fatigue due to rotor thrust. The input consists of the water depth, the turbine size, predominant wind speeds and 1- and 50-year wave return periods. Preliminary runs show that within the ranges applicable to the sites in the North Sea, changing the values of the wave return periods and wind averages have only a negligible effect of less than 5%. The used ranges for the parameters are based on the expected values in the Dutch part of the North Sea and can be found summarised in table 6.1. The ranges for the wind speeds are set using the Offshore Wind Atlas of ECN [64], and the significant wave heights are set using data from Rijkswaterstaat [204]. This is in correspondence to the study [80], where is shown that the design is determined more by fatigue than by extremes for a foundation of a 5 MW wind turbine at 25 m water depth.

In the model, the monopile is considered a tube: there is no transition piece added. For the mass estimation, an extra mass is therefore added for overlap and secondary steel. The overlap is taken as 1.5 times the diameter of the monopile D plus half a metre for the grout skirt [257]. The diameter of the transition piece is set as 30 cm wider than the diameter of the monopile, as the transition piece is expected to be connected over the monopile[21].

To test the accuracy of the model, a comparison is made to the foundations of several existing wind farms in the Netherlands, Denmark and the UK, as shown

[21] At the OWEZ park, the transition piece is placed inside the monopile.

Table 6.1: Tested ranges of foundation model parameters for the Dutch part of the North Sea. *Source:* ([165], [64]).

Parameter	Range	Dimension
Water depth	5 - 35	[m]
Turbine size	2 - 12	[MW]
Significant wave height 1-year wave return period	1 - 10	[m]
Significant wave height 50-year wave return period	1 - 10	[m]
Wind speed at 80 m	8 - 12	$[ms^{-1}]$

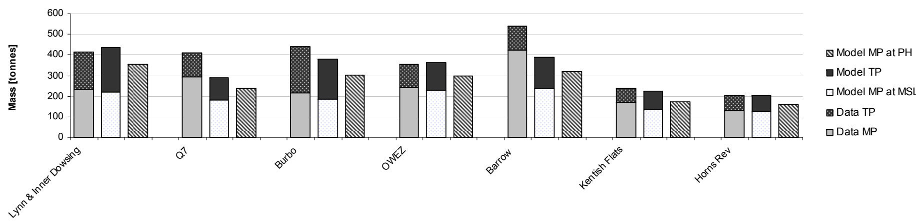


Figure 6.15: Comparison between model results and data mass monopiles.

in figure 6.15. All data has been gathered from websites of either the wind park or the supplier. For each site, the mass of the foundation is estimated in two ways. First, an estimation is made of the foundation using the water depth and platform height of the site and foundation data. In the figure, the bar '*Model MP at PH*'[22] represents this estimation of mass. In a second estimation, the foundation is calculated up to Mean Sea Level (MSL) and an estimation is made separately of the mass of a transition piece W_{tp} using the formula:

$$W_{tp} = (h_{ph} + h_{ol}) \cdot \pi \cdot (R_{outer}^2 - (R_{outer} - t)^2) \cdot \rho_s + w_{sec}, \tag{6.13}$$

where h_{ph} is the height from MSL to platform height, h_{ol} is the overlap with the MP taken at $(1.5 \cdot D + 0.5)$ metres, R_{outer} is the outer radius of the pile, t is the thickness of the pile is taken as $1/50$ of the diameter, ρ_s is the density of steel taken at 7,85 $tonnes/m^3$ and w_s is the extra mass of the secondary steel set at 5 tonnes.

The figure 6.15 shows that the model estimations without transition piece underestimate the published masses. When modelling the monopile and adding an estimation for the transition piece, the estimations resemble the monopile and transition piece data for most parks. The specific designs of the monopiles of the model are however quite different than the data: the calculated pile has a smaller diameter and higher thickness than the actual pile. The ratio diameter to thickness D/t is taken in the model as around 50, while in the data this ratio is at least 80. Two parks are clearly out of sync: Barrow and Q7. For Barrow, the extra mass could be partly caused by the longer monopiles that have been

[22]'MonoPile at Platform Height'.

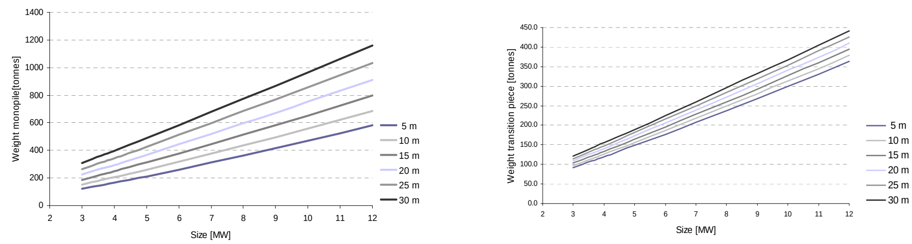


Figure 6.16: Weights of monopiles for the model input.

driven 30-40 metres into the seabed[23]. This could be due to the soil conditions of the Barrow site. The model does not take into account all load cases or the soil conditions.

Overall, the results with a transition piece look similar over a variety of wind turbine sizes and water depth and therefore the model has been used to create input for the model. In the input for the model, mass is calculated over varying turbine size and water depth, giving the lines in the figure 6.16. The following assumptions are made. The foundation is considered to run up to +15 m above MSL platform height. The overlap of the transition piece and monopile are again taken as $1.5 \cdot D + 0.5$. The average wind speed is taken as 9.5 m/s at 80 m and the significant wave heights are 3.75 m and 9 m for the 1-year and 50-year return period respectively.

6.3.8 The FoundationInstallation agent

The main resource of the FoundationInstallation agent (FIA) is its installation Vessel. The FIA makes a contract with an MCA for the transport from the harbour to the site and the installation of the monopile and transition piece using one of its vessels. The capacity for contracts of an FIA is restricted by the availability of his installation vessels. A Vessel has a cost of mobilisation C_{mob} and a day rate (including crew) C_{dr}. With the installation time per foundation as t_{inst}, a total cost C_{tot} can be calculated using:

$$C_{tot} = t_{inst} \cdot n \cdot C_{dr} + C_{mob}, \tag{6.14}$$

where n is the total number of foundations. The installation time per foundation consists of waiting on weather, the travel time, positioning time and the time to hammer or drive the pile; the latter is influenced by the diameter, thickness and hammer/drive height of the pile. The monopile can be driven 30 metres into the ground in about two hours [187] while the total installation time per foundation is around two days. The installation time per foundation is therefore

[23]Since the monopiles lengths are stated as 54-62 metres and the water depth is 15-20 m, the depth into the seabed looks to be more around 40 than 30 metres, which is certainly more than other sites.

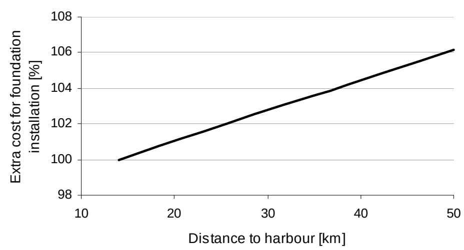


Figure 6.17: Foundation installation cost versus the distance to the harbour. The costs for a park at the same distance as OWEZ are set at 100 %.

seen as only dependent on the distance to the harbour, while the water depth and the dimensions of the foundation are neglected.

In the DOWEC project [195], it has been estimated that the installation of the foundations should cost 4.65 % of the total costs for a wind park. Using above formula and thus calculated foundation installation costs for OWEZ and PAWP gives an average installation time per foundation of around 2.5 days, where a dayrate and mobilisation cost are assumed of 100 k€ and 200k€ respectively. To take into account distance to harbour, a linear relation has been assumed and the foundation installation of OWEZ has been set to 100%. This results in the linear relation presented in figure 6.17. In the simulation, the initial foundation installation time is set to 2.6 days, and this is reduced by 5 % every year to represent installation innovation and learning.

6.4 Conclusions on the design of the agents

In the descriptions of some of the agents given in 6.3, the assumed bounded rationality in the actors can be seen clearly in the implementation of the agents. A Developer has limited information and calculation time to decide which site will be investigated in a basic design, as making a basic design for all sites is too costly. The Developer's investment decision for the chosen site is made using rules of thumb for payback times and expected cost and income. The implemented agents are boundedly rational, and procedurally rational. They can be risk averse or risk seeking in their investment decisions, reflecting their confidence in the market as a market party.

For the design of the agents, the steps of the methodology as depicted in chapter 3 (figure 3.5) have been followed. The use of use cases and interaction diagrams have proven useful. Certain (inter)actions follow protocols to mimic real-world procedures, albeit in a simplified manner. For example, parties developing an offshore wind farm are often joint ventures of companies including a public company (such as a utility) and project developers, and the participation of a public company requires European tendering of large contracts. This

European tendering is reflected in the model in the protocol used by the DeveloperAgent for tendering the turnkey contract. To simplify, only this tendering scheme is used by the DeveloperAgent to obtain a main contractor for the turnkey contractor.

Vertical integration is not taken along in this study. Veldman [245] states that there is not much vertical integration in offshore industry and it should therefore not pose a problem in simulation. However, some activities can be vertically integrated in one company, e.g. main contracting and foundation installation have been combined. Vertical integration could be integrated into the model in the same manner as an agent giving preference to a previous partner: in its contracting the contractor could take into account a cooperation preference based both on its contracting history and its initial preferences. A similar kind of preference structure between agents is addressed in landscape theory [17] where two parties i and j are given the propensity p_{ij} to cluster together[24].

[24] Landscape theory can for instance be used to model the creation of a coalition after national or municipal elections.

7

The Environment of the agents

Introduction

The Environment forms the surroundings of the agents from which they receive input. In this chapter the different environmental scenarios used for the runs of the simulation model are presented and it is explained how these environmental scenarios have been developed. First, the concept of environmental scenarios as introduced in chapter 3 is explained further. Second, the Environment of the Agents is delineated into four main groups: governmental policy, markets, North Sea locations and innovation. Several key elements will be chosen from these four groups. Third, different Environments are presented that will be used in the runs of the simulation model.

7.1 Making environmental scenarios

7.1.1 Environmental scenarios

When addressing the environment of the agents in the ABm as part of the model, it shall be written capitalised: the *Environment.* To develop different Environments for the simulation runs in a consistent way, scenario planning techniques are used. Porter's definition of scenarios was mentioned in chapter 3, stating scenarios as internally consistent views on a possible future [84]. As a scenario forms a view on a possible future, not a forecast of the future, several scenarios can be formed to span the future possibilities. The 'real future' might have elements from all scenarios. The scenarios made are environmental scenarios, depicting the surroundings or contextual environment of the actors in active roles. The scenarios consist of the factors that cannot be influenced by the involved actors but do influence them.

The scenarios will be built using a qualitative approach and the results will be quantified to act as input in the model. In a qualitative approach, scenarios are made as 'storylines': without the initial use of data, a possible future is described as an evolving story. Schwartz [216] developed a method using intuitive logics to build up this story as explained in chapter 3. The step plan for creating the environmental scenarios will basically follow his method, although one extra step is included: to determine the value of the key elements in high, medium and low values for the scenarios. The step plan is therefore as follows:

1. Determine the content:
   - Identify the key elements
2. Build the scenarios:
   - Identify the drivers
   - Choose the driving forces
   - Determine the values of the key elements
   - Create story lines
3. Evaluate the results

7.2 Determine the scenario content

7.2.1 Key elements: the four sectors of the environment

In the description of the agents in the previous chapter the required input for the agent was sometimes mentioned. For example, the Developer agent requires information on the locations in the North Sea and electricity prices. Here the input from the Environment is described, as a selection of the external factors and representation of the passive roles. This of course should fit the desired input of the agents as already identified in the agent design and follows the focus of the study, defined in chapter 4 as: permit procedures, financial support, layout and timing of an offshore grid, the availability of resources, specifically the wind turbines, innovation of the wind turbine. The permit procedures, financial support and offshore grid arrangements are part of governmental policy, while the availability of resources is connected to the (global and European) markets. The scenario content will therefore be from four different kinds of sectors: the North Sea locations, governmental policy, markets (wind turbine, materials and electricity prices), and innovation of the wind turbine.

7.2.2 North Sea locations

In total 58 locations in the North Sea are given as input to the model as possible park sites for agents of the type Developer to choose from. These locations have several site parameters: water depth, average wind speed and a geographical location. The geographical location of the possible park site is described as one single point representing the middle point of the location. The locations are given in UTM reference, specifically the ED50 and WGS84 as these are the most relevant UTM references for the North Sea[1]. The coordinates of the locations make it possible to calculate the distances, such as the distance to the coast.

The Dutch coast has been linearised for the calculation of the distance to the coast. The distance to the coast is the minimum distance from the point perpendicular to the linearised coast. In this manner the offshore connection is determined with a minimum length of offshore cable. The onshore landing point is used to calculate the distance to the onshore high voltage station. This is a simplification deemed justified by the lower cost of onshore cable versus offshore cable[2]. Since the shortest cable is not always possible[3], 15 % is added to the length of the export cable for the calculation of its cost.

About half of the locations chosen are the locations as defined in the submitted initiatives in 2005. Although there are 70 initiatives, taking into account the overlap reduces the number of locations to 28. In case of overlap, the first initiative is chosen as the reference location. When adding together the suggested installed power in the initiatives it can be derived that these locations already offer room for about 10 GW of offshore wind power. However, the majority of these sites are situated in the search areas as defined in the National Water Plan [152]. To also include sites situated in the preference areas, 30 extra locations have been added. In figure 7.1 the locations are shown graphically.

7.2.3 Governmental policy

Several parameters are included in the scenarios to represent governmental policy relevant to offshore wind. These parameters represent the grid arrangements and the portfolio requirements as input to the GridOperator, and the permit and subsidy procedures as input to the PermitOffice and SubsidyOffice.

Grid arrangements and portfolio requirements

The grid arrangements are handled during a simulation by the GridOperator agent. The four locations of onshore high voltage stations are given as fixed

[1] The WGS84 and ED50 are also the UTM systems used in the initiatives of the project developers.

[2] If it can be assumed that the onshore cable cost per length is half of the offshore cable cost, the simplified calculation gives the lowest price for most locations. For some Northern fields, the onshore distance from landing point to HVS is around 70 km and the locations are around 50 km off the coast.In these cases the cable costs will be overestimated when the shortest offshore distance is selected, but within the general precision level taken in this study it suffices.

[3] E.g. due to environmental restraints.

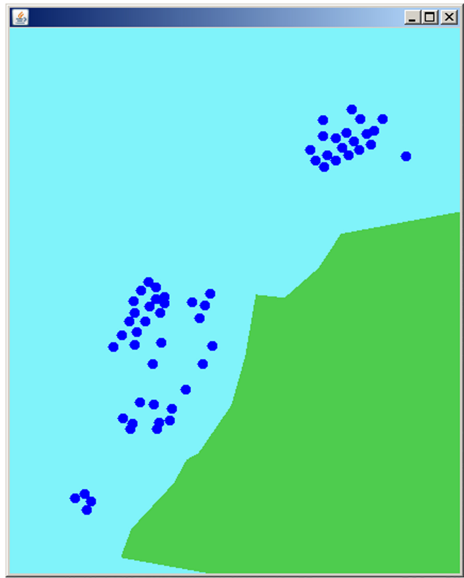


Figure 7.1: Locations in simulation model (screenshot). Note that the coast has been linearised.

input. The chosen locations and timing of construction for offshore stations and the possible construction of the fifth onshore high voltage station differ in the scenarios. In the environmental scenario, the timing and order of the construction of offshore stations is prescribed and serves as input to the GridOperator. The timing and order can be connected to the environmental concern and long-term thinking in the society, reflecting in government policy and regulation. An offshore grid can be supported to create a consistent policy onshore and offshore and to create fair competition between onshore and offshore electricity generators. High electricity demand can also have a supporting effect on the construction of offshore stations.

Portfolio requirements could be set in the scenarios to the utilities, giving a better chance of a PPA between Utility agents and Developer agents as Utilities will be more eager. Whether or not these requirements are set mainly depends on the environmental concern in the Dutch society. Priority access of wind power, where all generated output of a wind farm is fed into the grid instead of offered into the electricity market by a Programme Responsible Party, could also become a reality if national or European regulation is set in place.

Permits and subsidies

The environmental scenarios determine which procedures have to be followed by the PermitOffice and the SubsidyOffice. The characteristics taken into account for the procedures for a permit and a subsidy are: rules for the amount of subsidy, order of the permit and subsidy request, and selection rules for sites. There are three options for the permit and subsidy procedures, as discussed in chapter 6: a tender for the subsidy, a return to the first-come, first-served policy or a change to a subsidy tender without the pre-requirement of a permit. The selection rules for sites are included as part of the permit procedure.

Each location is given an area code denoting the kind of area it is in. There are 7 groups of locations. Two groups represent the locations in the preference areas, see figure 7.2. Two groups represent the locations in the search areas. The last three groups denote locations from the initiatives that fall in neither preference nor search areas. The SubsidyOffice can use this area code to give preference to certain locations as specified in the subsidy tender criteria. The PermitOffice uses it to decide if the location can be given a permit and how long it will take to give out this permit. This runtime for a permit represent the time it takes the authority to judge the permit request, complete a consultation procedure and the time for the developer to process the required adaptations to the park layout. Which area codes are permitted at which runtimes will depend on the scenario.

The possibility of getting a permit in these areas depend on their ecological, economical and political *sensitivity markers*: qualitative values marking the sensitivity of the site concerning ecological, economical or political issues. The political sensitivity marker represents whether it is a preference area, search area or neither. The economical sensitivity is dependent on the proximity to harbours and the coast. The ecological sensitivity of a location follows the overlap with areas designated as ecologically sensitive by the government and NGOs. Several ecologically sensitive areas are relevant for the chosen locations. In the governmental planning document [143] two relevant areas are identified: the Brown Bank and the Frisian Front. These locations are also identified by several NGOs as ecologically sensitive areas specifically to offshore wind parks in 2005, in a study [228] that marked areas of possible high environmental effects for nature and safety. In 2002 the work started for the designation of North Sea Marine Protected Areas (MPAs) [59] following European Directives. In February 2009 the status was given in [35], where sites as the Brown Bank and Frisian Front Coastal area are again mentioned. Proposed sites by NGOs as extensions for further MPAs[4] could lead to the inclusion of the sites Zeeuwse Banks and Borkumse Stones ([228], [35]), in agreement with the suggestions in the study of Lindeboom [132]. In figure 7.2 the ecologically sensitive areas are given together with the preference and search areas.

In table 7.1 the results of the sensitivity markers for the 7 areas are given. This is a very coarse approach, as these markers are set up based on an area while per site within one area there can be great differences. However, for this study this approach is thought to give enough information to test the impact of

[4] Partly due to also taking into account the OSPAR guidelines

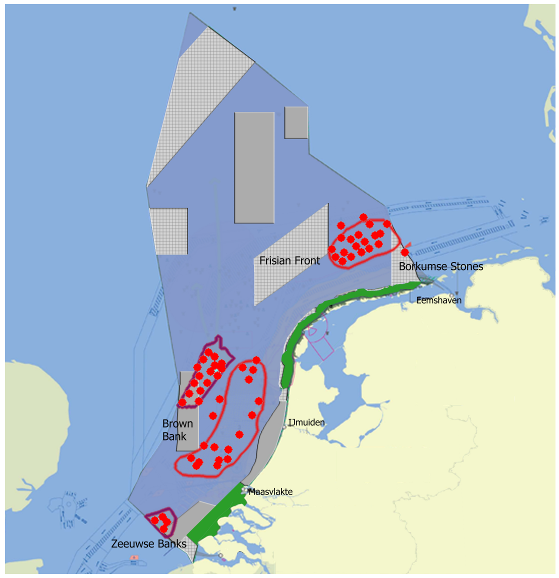


Figure 7.2: Locations, search areas and preference areas, and ecologically sensitive areas.

a permit procedure concerning runtime and approval, and the study focusses on the overall implementation as a total of installed parks instead of the specific locations of individual parks. The qualitative scale varies from a very negative assessment of the area (–) to a very positive assessment of the area (++) from ecological, economical and political perspective.

7.2.4 Markets

The development of price in or demand in several markets will be included in the model. The previous chapter, chapter 6, determined which prices and sizes

Table 7.1: Ecological, economical and political markers for the seven groups of locations. Here, the scale is given as –, -, 0, +, ++, representing very negative to very positive relative assessment of the site according to that marker.

Area	Ecological marker	Economical marker	Political marker
1	-	0	++
2	-	0	++
3	0	-	+
4	0	0	+
5	-	0	0
6	-	-	0
7	0	0	0

should be included as they form input for the agents: the electricity price, the steel price, and the global sale of onshore and offshore wind turbines.

Electricity price

The Environment provides a base electricity price input, which a Utility agent uses to determine the price it can offer a Developer agent as a kWh price in Power Purchase Agreements (PPAs). It also takes into account whether wind power is prioritised and if portfolio demands are set by the GridOperator, as it will want to avoid having to pay fines. Here the possible values of this base electricity price input will be determined.

Four main influences on the electricity price can be illustrated by a supply curve for the Dutch electricity market, see figure 7.3 where an estimated marginal supply curve for 2020 is depicted. The crossing of the marginal supply curve with the baseload demand (left vertical line) and peak demand (right vertical line) set the electricity price for all generators at baseload and peakload hours respectively. First, rising prices for fossil fuels will drive up electricity price, as the marginal supply prices increase. In 2010, approximately 50 % of the electricity supply is generated by natural gas in the Netherlands, while according to Seebregts et al. [218] around 2020 approximately 30 % and 35 % will be generated by gas and coal respectively. The gas price will therefore have a large influence on the electricity price and estimates for the depletion of the Dutch natural gas reservoir in Groningen vary from 2030 to 2050. Second, an increased electricity demand will increase prices, as the vertical bars representing off-peak and peak demand will move to the right, to the use of more expensive generation units and a high energy and electricity demand will increase the depletion rate of reserves, raising the prices of fossil fuels such as natural gas. The electricity demand is related to the economic growth [218], as high economic growth raises electricity demand.

Third, environmental protection measures can be adopted that raise the cost price of electricity. Several environmental protection measures can be and have been taken to make the 'polluter pay', as for example the CO_2 certificates scheme. This is seen as an efficient scheme for setting the price for pollution, the CO_2 emission. However, in the Netherlands CO_2 emission rights have been given by grandfathering and the CO_2 prices can therefore not be included as a similar rise in the production costs [217]. Inclusion of externalities and energy taxes would work in the advantage of wind energy as it improves the relative price of wind power generated electricity versus fossil fuel generated electricity. The level of incorporation of such regulation and legislation is dependent on environmental concern. Fourth, one can see that more wind power will lower the overall electricity price. Due to the low operational cost of wind power, traders will want to trade wind in the market at a low price to be sure it is in the collection of selected generation units to supply the demanded electricity[5].

[5] In [217] some other influences are mentioned: the market behaviour of producers, level of

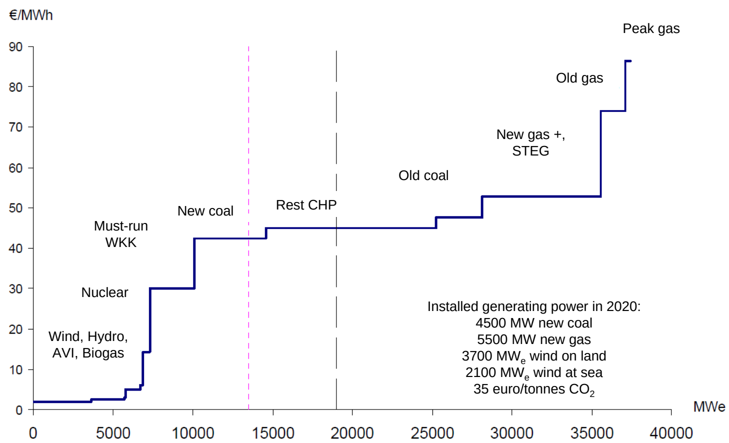


Figure 7.3: Illustrative marginal supply curves. The figure represents a scenario for the marginal supply curves in 2020 using 100 % availability and no export, with 5800 MW wind. *Source: ECN [218]*

This is reduces the electricity price as the marginal supply curve 'moves to the right'. This reduces the profitability of wind power, which is noted in several studies e.g. [13], [218].

Long term contracts representing contracts for baseload are used to examine the price that wind power generated electricity could receive, as these include the long term risks and inbalance costs a trader would have to take into account. These are also examined in for instance the unprofitable top calculations [217]. ECN has estimated the baseload prices in 2004 in [217] as 37 to 52 €/MWh for 2010 to 2020, while ECN estimations in 2010 in [53] go up to 62 €/MWh for baseload in 2020, as the average of peak prices up to 70 €/MWh and off-peak prices lower than 54 €/MWh in 2020. In a study on the future fuel mix in the Dutch installed generation units [218], price estimates are made using various scenarios[6] with varying CO_2 prices (20, 35 and 50 €/tonnes) giving baseload prices between 55 to 80 €/MWh. Compared to the baseload prices using a CO_2 price of 20 €/MWh, 15 and 30 €/tonnes extra CO_2 price give on average 5 and 10 €/MWh extra respectively on the baseload prices.

For the base electricity price, a high, medium and low development has been deduced from the numbers in the ECN studies, see figure 7.4. It has been explained that the electricity price is dependent on CO_2 prices, electricity demand, installed wind power and energy demand (fossil fuel prices), and therefore the consistent set of these parameters in each scenario will determine whether a

interconnection and the role of Combined Heat and Power (CHP) and renewable generation in mix.

[6]The ECN estimations use the CPB 'Global Economy' scenario, which has a relatively high growth in demand.

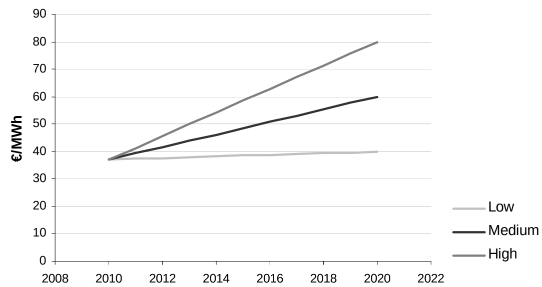


Figure 7.4: High, medium and low values for the electricity prices to be selected in the scenarios.

high, medium or low value for the electricity price applies.

All three price developments have been defined as simple linear functions going from a current price to an estimated price in 2020, even though the ECN estimates made using the POWERS model are not. However, here it is deemed better to test the impact of variable prices in a sensitivity analysis of the model parameter than to assume to know a specific course. The chapter 8 will include a sensitivity analysis.

Steel price

The steel price is a required input from the Environment, and affects the foundation and turbine prices in the model. For the foundations, the steel for the monopiles costs in the order of 1.5 €$/kg$ (August 2007 [157]). The steel price has fluctuated heavily in 2005-2010, as can be seen in figure 7.5, and for 2010-2020 as much variation can be expected. In the beginning of 2010 the price level is nearly equal to the price level of 2005. A lower and higher estimate is made for the steel price , where the low estimate is set at 80 % and the high estimate at 120 % of the 2010 prices. This gives a range for the monopile steel of about 1.1-1.6 €$/kg$. In the sensitivity analysis higher and lower bounds will be examined of 60 % to 140 % (0.8-1.9 €$/kg$).

Total installed wind capacity

The agents of type ContractorAgent use the data for the total installed capacity of offshore wind to make their own estimates of the size of the future market. This determines their confidence in offshore wind investments and influences therefore their own investment decisions and their profit margins. The agents of type TurbineSupplier regard the offshore and onshore wind installed capacities to determine the growth of their Factory capacity and how much of their Factory capacity they want to use for offshore wind turbine manufacturing. These agents therefore require input data from the Environment on the onshore

Figure 7.5: Price index of rolled steel plates (single hot roll) from January 2000 to February 2010. The index is set to 100 for the average price in 2005. *Source CBS StatLine [227]*

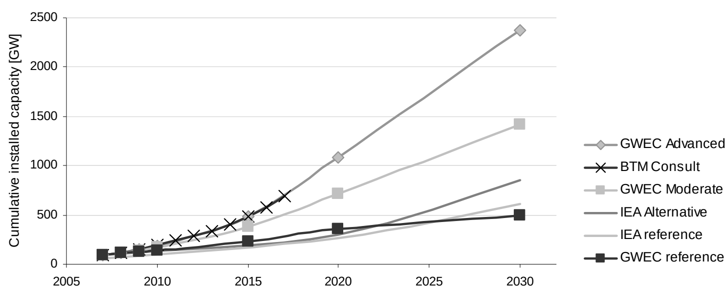


Figure 7.6: Forecasts for global cumulative installed wind capacity. *Source: ([72], [47], [110], [30])*

and offshore wind total installed capacity.

For each scenario, a different future installed capacity of onshore and offshore wind is estimated. A high, medium and low estimate is made using estimates from different organisations. In figures 7.6 and 7.7 forecasts are given for the respective onshore and offshore cumulative installed capacity up to 2030. Figure 7.6 depicts the global estimate, as wind turbines are sold in a global market and manufacturers will take into account European and non-European markets. Figure 7.7 shows, however, only estimates of the European offshore installed capacity. Almost all offshore wind energy is installed in (North-West) Europe, and it is to be expected that in the coming decennium this will remain the largest offshore wind market. The lack of available global estimates is therefore considered to have a negligible effect for this study.

Using these forecasts, the following high, medium and low graphs have been made to serve as input data: figure 7.8 for onshore, and for the offshore market figure 7.9. The low estimates represent the more conservative estimates of the

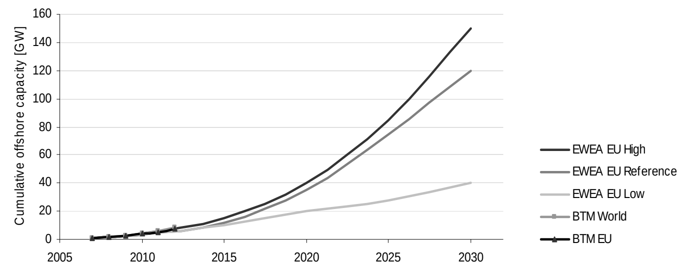


Figure 7.7: Forecasts for cumulative installed offshore wind capacity in Europe. *Source: ([72], [30])*

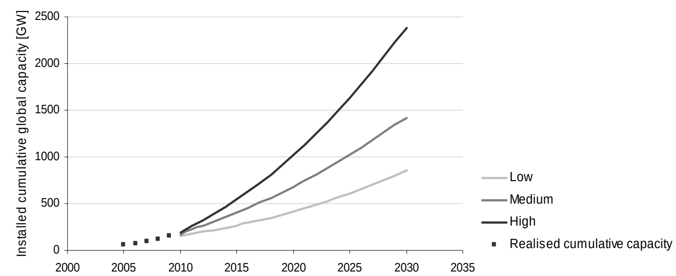


Figure 7.8: High, medium and low estimations of total installed global wind capacity.

IEA and the moderate scenario of GWEC. The medium and high estimates for onshore follow the GWEC reference and advanced forecasts. For offshore, the estimates are made using the EWEA and BTM forecasts, where the medium level is taken as a more conservative estimate in between the high and low estimates, instead of the EWEA reference estimate.

7.2.5 Wind turbine innovation

It is not possible to incorporate specific new concepts or breakthroughs which are of yet unknown. In the model, technological innovation of wind turbines will be incorporated on a higher level instead, in these two ways: the wind turbine size development estimations (individual installed capacity) and the wind turbine cost development estimations. Both will be used as a base development path for wind turbines for the TurbineSupplier agent, who uses this base development to determine its price and size of a new turbine. The prices and sizes actually occurring in the simulation will be dependent on this agent type's choices. The estimations will be based on gathered data and turbine size and price development as mentioned in other studies.

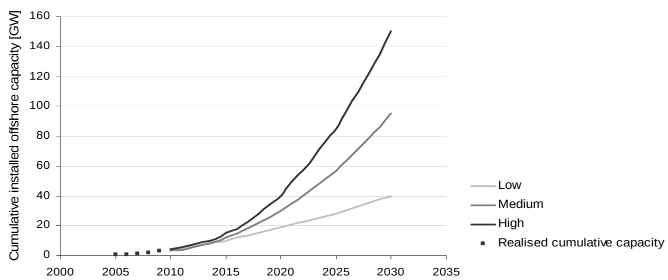


Figure 7.9: High, medium and low estimations of cumulative installed offshore global wind capacity.

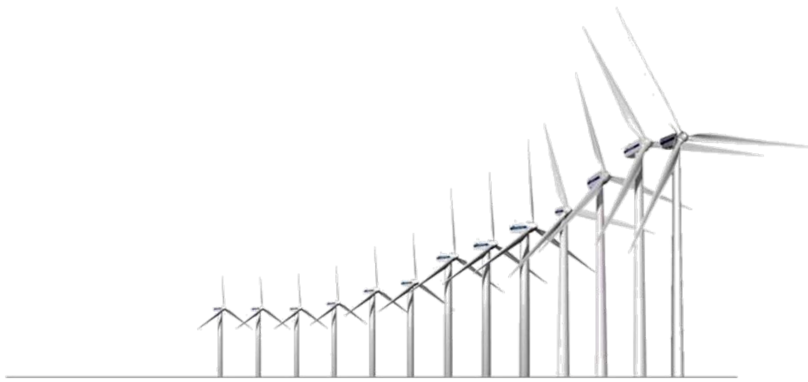
Turbine size development

Most likely, the three-bladed HAWT will still be the main wind turbine concept by 2020. The growth in power of these turbines is related to the size of the blades. When the turbine is considered as an actuator disc, the power that can be extracted by the rotor P_{wt} is proportional to the square of the diameter d: $P_{wt} \sim d^2$. In practice, the required diameter for a certain rated power is dependent on the efficiency of the turbine and on the site, since the rated power is also dependent on the prevalent wind speeds[7]. In [72], the relation is estimated as $P_{wt} \sim d^{2.4}$: due to wind shear[8], the data shows the actual power is proportional to d in a power larger than 2. However, offshore the wind shear effect is lower and for the larger turbines (usual for offshore application) the relation is closer to the theoretical $P_{wt} \sim d^2$. As an example, the wind turbine manufacturer Vestas and its product line is considered, see figure 7.10. Vestas had the largest market share for wind turbines from 2000 till 2012 [221]. For the product line of Vestas, the relation between P and d are fitted as a power function $P = Cd^m$. The data fits close to $m = 2.13$ or $P_{wt} \sim d^{2.13}$, see figure 7.11.

In figure 7.12, the Vestas data is combined with data from other manufacturers of large turbines of the last decades. The mentioned dates are the dates of the prototypes for mentioned turbines. It will take around 2-4 years for a prototype to continue to commercial production [247]. As model input, the dates of commercial production for a base wind turbine rated power are used. For the start date, 2005, the base rated power in commercial production has been chosen as 2 MW. This is approximately the average value of introduced prototype rated power in 2001, see figure 7.12. For the model input value towards

[7] For example, Siemens has in its product line three 2.3 MW turbines, with a 82, 93 and 101 m rotor diameter dependent on the site wind climate. Enercon has upscaled its 126 m rotor diameter wind turbine several times by improving efficiency, from 4.5 MW to 7+ MW, while retaining its 58 m long blades. The Enercon 126 is the largest turbine available in 2010, but has only been applied onshore.

[8] The wind speed is slowed down by the ground and its structures, and therefore the wind speed is higher at greater heights.



Product/Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2000	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1750	2000	3000
MWh/year	217	265	301	346	481	647	1304	1581	1947	2530	4705	6768	9152

Figure 7.10: Development of size for Vestas wind turbines. *Source:* [253].

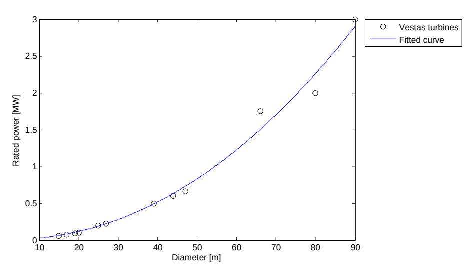


Figure 7.11: Rated power versus diameter. For the turbine types of Vestas, the d versus P is fitted with a power function $y = a \cdot x^b$. The fitted curve has $b = 2.13$.

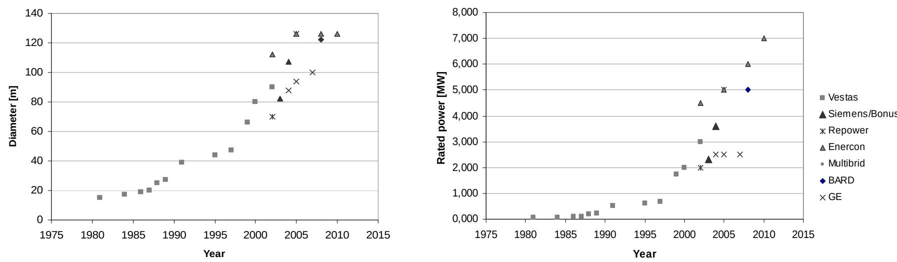


Figure 7.12: Wind turbine rated power and diameter in the years.

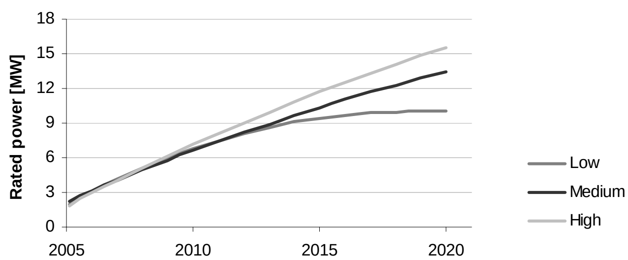


Figure 7.13: Development of turbine rated power.

2020, future estimations have to be used. As part of Innwind, a PhD research ([10], [11]) focuses on the economical and technical constraints to upscaling the current three-bladed HAWT, specifically the NREL 5 MW design, including e.g. fatigue, deflections, natural frequencies and the levelised cost of energy. In this study, the limit for upscaling is expected to be at around 12 MW with current manufacturing technologies. Ashuri estimates the range of wind turbine size in series production in 2020 to be somewhere between 12 and 15 MW.

For the model, the development of growth in power with a time horizon of 2020 is estimated in low, medium and high curves based on the considerations mentioned above. In the low and medium option, the rated power is estimated using an estimation for the diameter growth and the relation between power and diameter, using an estimated two years of experimenting between prototype and commercial production. In the low option, the diameter curve flattens, while in the medium option the diameter continues to grow linearly. In the high estimation a curve is fitted through two future points, a 10 MW commercial turbine in 2012 and commercial production of 15 MW in 2020. This leads to the low, medium and high estimations for wind turbine rated power as input for the model shown in figure 7.13.

Wind turbine cost estimation

The prices for wind turbines are not publicly available information, and here this cost is estimated using the total investment costs and expected percentage for wind turbine costs. Junginger ([120], [118]) has estimated the cost per main component (turbine, foundation, grid connection and installation) using experience curves and qualitative information for cost reduction possibilities. Junginger's estimates for investment costs stated an initial 1600 €/kW for a base case wind park of 400 MW at 20 m deep and 40 km of the coast at a time horizon in 2003 dropping to 980-1160 €/kW in 2020. The costs for the turbines are initially 47 %, about 750 € per kW. However, material prices and market stresses have shown his estimates to be too low. The two Dutch parks have been built for considerably higher total investment cost: about 1900 € per MW for OWEZ in 2006 and about 2900 € per MW for the Princess Amalia park in 2008, with an estimated 46 respectively 41 % of the investment representing the cost of the turbines [157] (about 830 and 1250 €/kW).

Other studies have shown a variety in total investment costs and the turbine costs for supply and installation have been estimated to lie around 30 to 50 % of the overall investment costs of an offshore wind park ([72], [120]). The European Wind Energy Association (EWEA) published the investment costs of ten parks installed between 2001 and 2007 in [72], where the parks ranged from 23 to 180 MW installed capacity. The investment costs per MW range from 1.2 to 2 million € per MW, leading to an estimation for wind turbine cost of 0.6 to 1.0 million € per MW. Some of these parks are in more sheltered waters, however, than the North Sea. The Dutch government has funded several cost estimation studies to calculate the unprofitable top[9]. ECN performed these studies, and in 2003 [210] the investment costs were estimated as 2 € per MW. In 2006, the study [236] for unprofitable top raised its estimates to 2.2 €/MW as a basis for 2008 subsidies, based on noted range of investment costs as 1650-2250 €/kW. However, in the final advice [235] the estimations for offshore wind were not included as they would be calculated in a later stage after more information was available. The stated reason for this was the unclear view on the risks of an offshore park, and with experience gained these should become clearer. However, not just risk but also a rising steel price and a sellers' market can drive up the price, as experienced around 2007. The steel price has a large impact on turbine price as steel is a main material for turbines, as for instance towers and constructional parts of the nacelle are mainly steel.

As one can see, wind turbine costs are subject to great uncertainty. In fact, presuming the cost to develop in manner of € per MW is in itself unreliable, as for instance the per unit cost of the 3 MW wind turbine of OWEZ has been almost equal to the per unit cost of the 2 MW wind turbine at PAWP. Also, large orders can give reduction of around 30 % of catalogue price size of wind

[9] The difference between income and costs of a wind park, to determine the required height of the (MEP) subsidy.

park matters. For the model input of base price, and will decrease in time to show cost reductions due to learning. The start value (in 2009) has been set at 900 € per kW. The price development follow the learning curves for cost reductions (using the installed capacity estimations) at a progress ratio of 85 to 90 %. This base cost does not include profit margins for the TurbineSupplier; dependent on the market stresses (higher demand) the TurbineSupplier agent will ask higher profit margins.

Notes on wind turbine innovation

The cost and individual installed capacity development estimates have been set at the beginning for the simulations in 2007. In 2012, the prices have not gone down, but gone up. In the input, progress ratios and learning had been assumed for decreasing prices, but technical risks and market stresses have increased the price, and the size of the wind turbine itself has increased its price as well: for large wind turbines, the price per MW has increased instead of decreased. One of the reasons is that larger turbines need stronger materials, for instance carbon blades. The installation and foundation cost per unit still make a larger wind turbine interesting. This effect has not been taken into account, and the author therefore expects the turbine prices to be underestimated in this study.

The values for the individual installed capacity the author considers too optimistic now. In the chosen input values, the 7 MW wind turbine is shown as in commercial production in 2012 and would therefore be considered for offshore wind farms. However, for planned offshore wind farms in 2012/2013, a 6 MW wind turbine is the largest wind turbine named as a possibility. The rising prices per MW for ever larger offshore wind turbines might cause the rated power of a wind turbine increase to slow down: perhaps the rated power of a wind turbine starting series production in 2020 should have been set to a more conservative low/medium/high of 7/9/12 MW.

7.2.6 The chosen key elements

The key elements for the scenarios can now be summarised from the markets, governmental policies, North Sea locations and innovation. The water depth, UTM location and average wind speed for all North Sea locations are fixed input for all scenarios. In the three remaining categories, a total of 12 key elements have been identified as inputs to be included as parameters in the Environment:

- Policy
  - permit possibility per area
  - runtime of permit request
  - subsidy amount
  - portfolio requirements
  - priority access

  - offshore grid layout
- Innovation
  - average wind turbine power
  - base wind turbine cost
- Markets
  - electricity price
  - steel price
  - onshore market
  - offshore market

7.3 Building the environmental scenarios

7.3.1 Driving forces

Theoretically, if the twelve key elements can take three values, this would give $3^{12} = 531,441$ different environmental scenarios in a purely quantitative approach. To reduce this to a workable number instead, a qualitative approach is adopted to find combinations of values of variables that would create interesting and consistent scenarios. For this the large forces or mega-trends in the socio-technical system are examined that influence all these parameters: the driving forces. Using two or maximum three such drivers gives rise to 4 to 8 scenarios. The drivers should be independent from each other, otherwise it is better to group drivers into one, to get scenarios that are as different as possible from each other.

Several driving forces can be seen as relevant. In the description of the key elements, some influences have been mentioned on the values of these key elements such as environmental concern. Previous studies in scenario analysis for Netherlands have identified relevant general driving forces for the Netherlands. Two driving forces are used by the CPB in their 'Four Futures of Europe' [154], where international cooperation versus national planning and private versus public responsibilities are used to lead to four scenarios. The four scenarios (Global Economy, Strong Europe, Regional communities and Transatlantic Market) have been used in other studies as well (e.g. in ECN unprofitable top calculations, as for instance [53]). In the energy scenarios of the Ministry of Economic Affairs [177], looking into the possible development of Dutch society and energy consumption, four scenarios were developed using the axis of driving forces of international versus national cooperation and the focus on long term versus short term thinking. The long term thinking leads to more attention to the environmental impact of human activities and, dependent on an international or national focus, leads to global or regional solutions respectively.

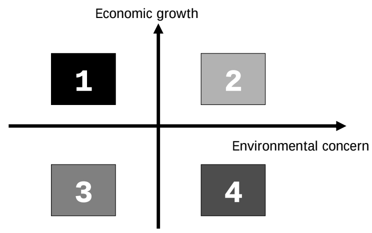


Figure 7.14: The two chosen drivers and the resulting four scenarios.

7.3.2 Choosing the driving forces

The examples above already mention some possible driving forces. Three drivers can be seen as especially relevant for this study: low or high technological innovation, economic growth versus stagnation and environmental concern. The latter can be seen as a socio-institutional driver, where society support for green development translates to institutional support for Renewables in general and offshore wind in particular. The first two drivers are considered dependent, as periods of high economic growth will often make higher R&D budgets possible which supports technological innovation [58]. Therefore these two will be combined and two drivers remain, along which four scenarios can be created using the drivers, see figure 7.14. Before the scenarios will be presented, the values of the key elements will be chosen within each quadrant to form consistent sets.

7.3.3 Choosing the values of the key elements in the scenarios

For each scenario the parameters will be evaluated to see which value would be consistent within the scenario. For each driver the effect on the twelve key elements has been examined to determine if a high or low development of this driver will have a positive (+1), negative (-1) or neutral (0) effect on the key element. In table 7.2 the results are given. This is used as a basis to decide the values of the elements in each scenario.

The values for key elements in the four scenarios are depicted in a spider plot, see figure 7.15. The axes of the spider plot use an ordinal scale, meaning the scale represent a ranking of greater and smaller but the intervals do not represent a certain value. The values across the scenarios show a nice spread, indicative of variety in the scenarios. Some elements are deemed independent of a certain driver, e.g. the steel price is assumed to be independent of the environmental concern driver and is therefore determined by the economical growth and technological development only. This is because the steel price is seen as mainly dependent on industrialisation, which is connected to economical growth.

Most inputs have been presented in a low, medium or high version and the

Table 7.2: Effect of the main drivers on the key elements.

	Environmental concern		Economical development	
	High	Low	High	Low
maximum installed power	-1	1	1	-1
permit runtime	1	-1	1	-1
subsidy	1	-1	1	-1
portfolio	1	-1	0	-1
offshore grid	1	0	0	-1
electricity price	0	0	1	-1
steel price	0	0	1	-1
onshore market	1	-1	1	0
offshore market	1	-1	1	-1
average unit power	1	0	1	-1
wind turbine cost	-1	1	-1	1
priority	1	-1	0	-1

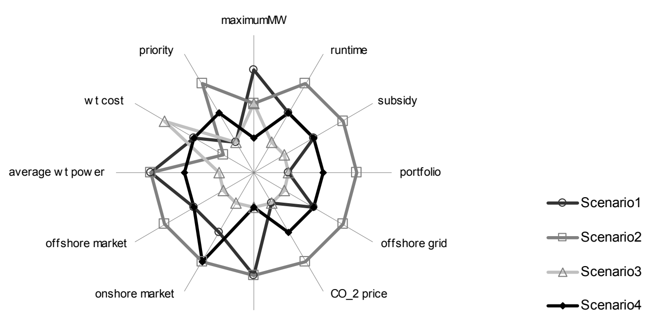


Figure 7.15: Spiderplot of the key elements for the environmental scenarios. Values are represented on an ordinal scale, from a low value in the centre moving outwards to a higher value.

Table 7.3: Maximum installed power per cluster as implemented in the PermitOffice agent, dependent on the environmental scenario in the run.

	Max allowed installed capacity per area for scenario: [GW]				Max possible [GW]
Area	1	2	3	4	
1	3.0	3.0	3.0	3.0	1.4
2	1.5	2.0	1.5	2.0	4.7
3	0.5	0.5	0.5	0.5	0.7
4	1.5	0.0	1.5	0.0	2.1
5	1.5	1.5	1.5	1.5	3.5
6	1.0	3.0	2.0	3.0	6.2
7	1.0	3.0	1.0	1.0	0.7
8	1.0	3.0	1.0	0.0	0.4

-1, 0, and 1 can be interpreted as these low, medium and high versions. For the governmental policy, sensitivity markers had been introduced in section 7.2.3. Using these sensitivity markers, the possibility of obtaining a permit and the associated permit runtime have been determined for each site in each scenario. The impact on the possibility of obtaining the permit has been interpreted in a maximum allowed installed capacity per area. For each scenario a maximum amount of installed capacity has been determined for each cluster. In some scenarios certain locations are excluded from attaining a permit altogether. As an example, in scenario 1 the maximum allowed installed capacity for cluster 2 (the close western locations) is 1.5 GW, while the summation of surfaces of all locations in this area would allow a maximum of 4.7 GW of installed capacity[10]. The limitation to 1.5 GW represents the importance of this area economically, taking precedence over other considerations.

7.3.4 Scenario storylines

Scenarios are often 'dressed up' to complete storylines. This helps in communicating the scenarios, as stories are easier to share than a collection of key elements and their chosen values. Also, scenarios can gain in support if it made clear how they could come about. In writing the storyline, the scenario can be checked for inconsistencies, for instance in the values of the key elements versus the relevant value of the drivers forming the main axes for all scenarios. The scenarios can be supported by graphs to help visualise the developments.

Here the scenarios will be presented in only a mild 'get-up'. The storyline of the scenario is used to explain the link between the values of the key elements and the values of the drivers that are chosen as the main axes only. The scenarios presented here therefore only lightly sketch the future image, to clarify

[10] A power density of 7.0 MW/km_2 is used.

the differences in the scenarios and to provide a consistency check. Graphical support is not used, as not to repeat the graphs already presented in this chapter.

7.3.5 The environmental scenarios

1 Individual development

High economic development - Low environmental concern
In the early 2010s, the credit crisis evaporates in rapid pace. The new confidence in the global market gives high consumer enthusiasm translating into a high energy demand, causing high electricity prices. The crisis did leave its mark on the environmental concern, there is now more concern for the here and now than the long term climate issues, and distrust in the 2012 IPCC report because of new found mistakes do not turn this new tide. High economic activity keeps a high demand for steel, which fluctuates between high and very high prices.

The high economic development has spurred technological innovation, and new innovations spark upscaling of the wind turbines. This reflects in the international offshore and onshore wind turbine markets, although they are tempered by the low environmental concern and lack of EU Renewables regulation. Despite the low focus on 'green', the high electricity demand and high innovation has still increased the wind turbine market, although the interest in offshore wind has only grown since the large wind turbines came on the market. Some cost reductions in wind turbines are made thanks to this market increase, as well as the use of new materials.

The government is not focused on making regulation to support green development and there are no new EU regulations tying them down. Offshore wind is therefore not supported by measures such as priority access for wind generated electricity. The low interest in long term solutions has caused an impasse in the permitting and subsidy system for offshore wind parks. Only later are the procedures set in order because of the increasing electricity price and electricity demand and the concerns for rapid depletion of oil and gas encourage offshore wind development. The run times become fairly short and as long as a site does not damage the economic interests of harbours it will obtain a permit. Instead of financial support in the form of subsidies covering the full unprofitable top, portfolio demands to utilities are presumed to support offshore wind development. An offshore grid in limited form is implemented to support offshore wind concentration outside areas of economic interests and to increase connections to Great Britain and Denmark.

2 The Sky Is The Limit

High economic development-High environmental concern
The progressive coalitions in the second decade of the 21st century are successful

in achieving a high economic development while looking out for the environment. Long term thinking and climate change concerns from society translate to new governmental measures to support greener surroundings, such as support for electric cars. While the latter increases electricity demand, on the other hand the cumulative effect of small measures such as banning ‘standby functions’ have tempered the demand. Still electricity prices are high also due to the high CO_2 prices.

The high economic development has spurned new concepts and solutions. The size of a wind turbine has increased dramatically. The cost of a wind turbine suffers under the high steel prices, but the new concepts have overall cost-reducing effects. The positive developments in the sector and the high focus on Renewable technologies have supported an increase in the onshore wind market and the offshore market, also outside of Europe.

The subsidy system and permit procedures are set in place to support high growth of offshore wind. A new permit procedure for parks reduces unnecessary costs for developers and the runtimes are reduced by the one-stop-shop procedure as now a single governmental office is in place for all questions of developers, which gain confidence in the Dutch offshore wind market. For parks in environmentally sensitive areas, permitting is harder and compensation requirements are high.

The Dutch government has ordered the layout of an offshore grid to support offshore wind development, decrease the effects of dune crossing of several cables, and to make certain areas more attractive. The decision to go for an international offshore grid causes some grouping in the permitting preferences of parks. Wind power generated electricity has priority access since 2018, making it easier for utilities to sell their wind generated electricity and fulfill their portfolio requirements. These portfolio requirements are set as a required percentage of green electricity in the total installed power/generated electricity.

3 Economic inertia

Low economic development - Low environmental concern
The prolonged crisis has pushed back long-term thinking and the environmental concern is low. The faith in the economic system goes down and not many companies dare to invest. Energy saving measures are taken to cut costs. The growth of the electricity demand and electricity prices have gone down slightly. Due to lower demand, material prices for materials such as steel have also stabilised at a lower price.

Due to the economical slump, no policy incentives or regulation has been agreed upon on a European level, and also on a national level no extra arrangements are made for Renewables. Therefore priority access is not set for wind generated electricity and the utilities face no governmental portfolio demands.

Due to the low technical innovation, the upscaling of wind turbines has slowed down considerably and this lack of push from innovation and policy has slowed down wind turbine market growth, also resulting in a slow-down of wind turbine cost reductions.

Due to the low environmental concern and low technical progress, there are no real restrictions on offshore wind park size. The permit run times are low and the permit probability is high, as economic activity on the North Sea has diminished. But the subsidy amount is low, as the government does not make wind at sea a priority subject and it also does not invest in an offshore grid before 2030.

4 Saving green

Low economic development - High environmental concern
As global warming becomes more visible, society becomes more concerned for the environment. Economic activity is low, however, restricting governments in the execution of environmentally friendly regulation. Focus lies on saving energy, for instance by making people more aware of the large ‘electricity consumers’ in their house. The low economic activity and savings have a decreasing effect on the growth of the electricity demand, making it possible to have some mild ‘polluter pays’ regulation while keeping electricity prices at an acceptable level. Steel prices are at a lower level due to the lower industrialisation.

The environmental concern supports the growth for the wind market, although to a lesser extent to offshore wind due to the higher technical risks and costs. Landscape concerns still support some growth in the latter market. Although the markets are (fairly) good, this is balanced by slow overall technological innovation, leading to only moderate upscaling and cost reductions for wind turbines.

Measures for the support for offshore wind are taken but nothing too extravagant is implemented. A limited offshore grid, delayed priority access (after 2020) and moderate portfolio demands to utilities are decided upon. Permit procedures and subsidies are in place to support offshore wind and to support Dutch employment in this new sector. Runtimes for permit procedures are short, except for sites in environmentally sensitive areas. To avoid disruption to the sea life, only a limited amount of parks can be built per year.

7.4 Evaluation of the scenarios

Twelve key elements have been identified associated with the geographical locations, governmental policy, markets and technological innovation. The variation in these key elements over the four scenarios show that a span of institutional, technological and physical aspects are addressed in the environmental scenarios as desired for the background of the model, as the implementation is seen to develop in a socio-technical system.

To simplify the input for the model, several high-low or high-medium-low values have been deduced from data and literature. A reduction of possible parameter combinations has been achieved by choosing two drivers as axis for four environmental scenarios. As can be seen in the spiderplot of figure 7.15, these chosen drivers give a nice variety in the combination of values for the key elements, leading to four distinct environmental scenarios.

As always, delineation leads to simplification of reality. The number of key elements to be addressed in the environmental scenarios has been reduced to the set of elements presented in 7.2.6. Some aspects have been taken along indirectly, for instance CO_2 and oil and gas prices are only incorporated indirectly through the electricity prices. For a more detailed study, elements such as CO_2 price or the prices of materials other than steel (e.g. copper) could be included. That approach will require a more detailed view on parts of the socio-technical system under consideration than included in this study. The possible values of the key elements have also been simplified for the simulation, as two or three different values have been identified instead of a full development of that factor for each scenario. Sensitivity analyses are required to see the effect of (changing) the values of the elements. These will be part of the next chapter.

8

Results

Introduction

In this chapter the model will be showcased. The results of different simulations are presented to show possible variations in the model, to show the suitability of the agent-based approach. First it is explained what a basic run entails, by presenting the basic model parameters and typical steps in a run. Second, the verification and validation of this model is described. Third, the results are shown for a variety of simulations with the model, using the four different environmental scenarios from chapter 7 for the determination of the environmental parameters. Fourth, a sensitivity analysis is presented, presenting the simulation results when varying specific parameters. This chapter is concluded with a discussion of the results, reflecting on the validation and verification, the scenario runs and the sensitivity analysis.

8.1 Model

8.1.1 Basic set-up of a run

Each time step in the model represents one month. This time step length has been chosen as it represents the level of detail in the model at this point; it is close to the smallest relevant time duration of the different processes taken along in the simulation. Some rounding of process run times is required for certain processes incorporated in the model. For example, in the model MainContractors have to respond to a call for tender if they want to be invited to participate in a tender. In European tendering, the minimum time for the receipt of requests to participate in a tender from the publication date announcing the upcoming tender is 37 days: this is rounded to one month in the model.

The simulation is run as a simulation starting from the year 2005 up to the year 2020. The simulation starts back in time so real data of for instance ins-

Table 8.1: Number of agents of each agent type in simulations.

Agent type	nr.	agent type	nr
Developers	4	MainContractors	4
Utilities	4	EIAConductors	1*
OMContractors	4	TurbineContractors	4
TurbineInstallers	4	HarbourManager	4
FoundationSuppliers	3	FoundationInstallers	3
CableSuppliers	3	CableInstallers	3
StationSuppliers	3	StationInstaller	5
ElectricalContractors	3	OnshoreWorker	5

*: this agent type is not a strictly unique agent, but since it is given a low priority in the modelling, only one instance is created solely to represent the runtime of the actions of this agent type to the implementation.

talled capacity can be used and because the moratorium on offshore wind parks in the Dutch Exclusive Economic Zone (EEZ) was lifted in 2005. The end date is chosen to compare the installed power at the end of the simulation with the target of 6000 MW by 2020.

In chapters 6 and 7, the values of different input parameter have been discussed and presented, e.g. steel prices and internationally installed offshore wind capacity. These input parameters are environmental parameters or attributes of an agent type. The model has model parameters as settings for a specific run that previously have not been discussed: the number of agents, the behaviour type for each agent type, and the scenario number.

Number of agents

For the simulation runs, the number of agents of each agent type has to be set. Unless specifically stated, all runs will use the same number for each agent type, see table 8.1. This amount is considered a realistic number for that agent type. As stated before, the PermitOffice, SubsidyOffice and NationalGridOperator agents are unique agents: only one of each of these types is included.

Behaviour type

For the agents, four behaviour types have been implemented and specified in values of the behavioural input parameters. This behaviour type therefore determines the behaviour of the agents in a run, e.g. the maximum number of parks a Developer Agent wants to have in the planning phase. Each type is numbered and the four types represent: a risk averse agent (1), a risk seeking agent (2), an extremely risk averse or 'limited' agent (3), and an extremely risk seeking or 'unlimited' agent (4). The first two are used in the development path

Table 8.2: Main behavioural parameters for the Developer agent.

Behaviournumber	1	2	3	4
maxNrOfInitiatives	4	7	1	50
maxNrOfPlans	1	4	1	50
investmentYears	8	10	8	10
finishTime	2	3	2	3
profitMargin	0.11	0.9	0.10	0.10
preferredParkSize	100	100	100	100
sizeFactorNextPark	1.5	1.8	1.5	2

runs discussed in section 8.3, the latter two types are only used in the validation and verification presented in section 8.2. A fifth behaviour type (0) is the default behaviour type: the behaviour type if no behaviour type has been selected as input. This default behaviour either selects an average type of behaviour for an agent type or is a copy of another behaviour type (usually risk averse).

An example of the implementation of behaviour types for agents is given in table 8.2. In this table, the parameters of the Developer agent that vary for each behaviour type are stated and will be shortly explained here. The Developer agent has lists of parks in different stages. It will only examine up to `maxNrOfInitiatives` sites at all points in time, and it will only have up to `maxNrOfPlans` of parks in the stages pre-consent phase up to operation phase. This means that if the Developer agent has `maxNrOfPlans` of parks in one of these stages, he will not further examine a location in his initiatives list until one of the parks has been constructed or cancelled. The `investmentYears` represents the number of years in which the Net Present Value of the investment should become positive in order for the Developer to make a positive investment decision. The `finishTime` parameter represents the longest time the Developer allows in his tenders to finish a park, starting from the tender date. In all behaviour types, the Developer agents start with a preferred park size of 100 MW (`preferredParkSize`), but depending on the behaviour type the next park could be 150 to 200 MW, using the `sizeFactorNextPark`.

Scenario number

In the simulation run, the chosen scenario number determines the values of the environmental parameters. These values can be a certain single value, e.g. the single value of the progress ratio representing the progress in wind turbine technology, or a certain development over time, e.g. the steel price development, the total installed capacity of offshore wind energy in Europe. There are five scenario numbers: 0,1,2,3, and 4: the latter four numbers correspond to scenario 1 to 4 as described in chapter 7. The first represents a scenario setting where all the parameters are set to a level deemed most unlimiting. As an example; in scenarioNumber 0, the SubsidyOffice agent receives an unlimited budget for subsidies, and the PermitOffice agent will allow all sites for wind park locations.

After one time step (or in some cases after one year), changes in the agent's environment will affect its behaviour. For example, a wind turbine supplier agent can respond to a growing offshore wind market by increasing its factory capacity. The manner of change is determined by the chosen scenario number and behaviour numbers for the different agent types.

8.2 Verification and validation

8.2.1 Verifying and validating an ABm

The validity of a model addresses how well the model simulates the intended purpose, both in procedural sense and in the sense of the realistic values of results. Checking the model's validity therefore consists of two processes: the validation and the verification of the model. The IEEE defines (software) verification and validation as follows [111]:

> The verification process provides objective evidence whether the software and its associated products and processes conform to requirements [...] and successfully complete each life cycle activity [...]
>
> The validation process provides evidence whether the software and its associated products and processes satisfy system requirements allocated to software [...] ; solve the right problem (e.g., correctly model physical laws, implement business rules, use the proper system assumptions); and satisfy intended use and user needs.

In other words, the verification of a model entails confirming that the model functions in the manner as intended in the design of the model, while the validation of a model refers to checking whether the results of the model give realistic values in the use of the model. Verification and validation can be complicated because unexpected results can be due to errors or emergent behaviour, as stated in section 3.1.6. Therefore simple runs will be made for which the results are more predictable and all 'surprises' in all runs need to be checked. This check is made by going trough the code step by step and by making variations to runs with the unexpected results to try and find a reason. As will be seen in the model results, not all 'surprises' have been explained in this manner (see scenario run 4 in section 8.3.2). Typically, the validation and verification processes of a model take longer than the implementation of the model itself.

Various techniques for the validation and verification are applicable to the different parts of the model development process of simulation models [211]. There is less available literature on agent-based model validation and verification specifically[1], therefore more global methods from general simulation models are

[1] One notable example is [74].

used. In the following presentation of the verification and validation the chosen techniques will be explained and examples will be given.

8.2.2 Verification results

In verification, one can distinguish two approaches [211]: static testing and dynamic testing. In static testing the computer program itself is analysed. Dynamic testing refers to the analysis of the execution of the program under varying conditions. An example of a technique for static testing is code review, while dynamic testing includes techniques such as examining the trace[2] and using extreme conditions.

In [226], Smith mentions both a dynamic testing method and a static method to verify a model: unit testing and docking, respectively. In unit testing, the model is run after each modification to check for unexpected results. For agent-based models such unit testing can consist of testing the model after the inclusion of a new agent or a new procedure for an agent (including possible changes to other agents required by this new procedure or agent). Since the execution time of an agent-based model is usually fast[3], unit testing is a good technique to check for programming errors. Docking refers to developing the same model in a different programming language and a different ABM toolkit[4]. Redeveloping the model in a different ABM toolkit is not always feasible or practical considering time restraints[5].

For the verification of this model, the focus lies on dynamic testing, using traces, both as unit testing and overall model testing[6]. If unexpected situations turn up, warnings are written to the trace. The model is run after a new addition. Overall model testing is done using extreme conditions. The testing of certain parts of the model, e.g. certain methods of an agent or a certain communication between agents, can be made easier by excluding other influences on an agent or agents. The extreme behaviour types and the extreme environmental scenario are used to test if the investigated part of the model works in all circumstances. One example of using extreme conditions is given below.

---

[2]The trace is a collection of output lines to the console or log file to follow the execution of the program. The trace is used to check values and procedures, for instance by giving a warning message if code is entered that should never be entered.

[3]This is of course dependent on the specifics of the model, e.g. whether convergence is tested.

[4]Remember extendability is not a main goal.

[5]Attention has been given to the redevelopment of a model by others, called replication, e.g. in [261] and [16]. In [16], Axelrod replicated 8 simple models, and stated that the main difficulty was that often not the whole model was specified, not all data was given or a sensitivity analysis was not performed. Wilensky et al [261] note that replicating agent-based models can help to create standards.

[6]Note that static testing is also done by the IDE, for example it points out uninitiated parameters.

Verification example: Eager Developers and one careful MainContractor

In this example the postponement procedure of the Developer agent is checked. The extreme environmental scenario '0' is used to eliminate effects of permitting and subsidies, as in this scenario all permits and subsidies are awarded. In the run, several Developer agents are initiated and set to 'very eager' (behaviour number '4', unlimited) to build parks, while only one MainContractor is included and its behaviour type is set to '3', or in other words; not so eager. It is expected that this will lead to many postponed parks, as the MainContractor only responds to a maximum number of tenders at the same time. This maximum is based on the number of tender offers he already has made, his estimate of how often he will actually win a tender after making an offer, and the number of parks he already has under construction.

Running the model using these settings indeed leads to many postponed parks. The Developers often receive the message that no MainContractors responded to their tender and in response have to postpone their plans. Furthermore, the more Developers are included, the less parks are built: more Developers are competing for the time of the MainContractor. More Developers therefore leads to more unanswered tender invitations and after a second attempt a Developer cancels his efforts for that park. Note that it is assumed that the Developer agents do not know the reason why the MainContractor agent(s) do not respond, and do not know why other Developers cancelled a park for a certain site: his information is assumed limited.

8.2.3 Validation results

For the validation of agent-based models, one typically has to deal with the issues of comparability and complexity [74]. Comparability refers to the comparison of the model to other models or the expectations expressed in other literature. The complexity of the model can complicate finding other data to compare or to state 'what is to be expected', as one event can influence many others.

Validation is often performed using a business-as-usual case for the model and this is compared to another model's results or expectations stated before the simulation run. For this model, validation is performed by dynamic testing using such expected results and extreme conditions to create data that can be compared to literature. A business-as-usual model is created by setting the parameters as seen most fitting to the current state-of-affairs. A business-as-usual environmental scenario is made and the behaviour of the agents is set to a state which can be considered most neutral. For some inputs, highs, lows and medium settings have been chosen. Extreme conditions are used to create data independent of certain variables. The traces are read through for warnings and to check whether certain numbers are in a reasonable interval.

Validation example 1: 58 Developers

The main model output parameters include totals and averages (e.g. total investment costs and average park size) and the data of each constructed park. This park data entails dates for construction, the costs divided in categories and the distances to coast, harbour and grid. This data will be compared with data from other studies. A study from ECN [105] is used for a comparison of the park costs per location. In this study, locations for offshore parks have been estimated compared to the costs of the first Dutch offshore wind park, the Offshore Windpark Egmond aan Zee (OWEZ), using a 'standard' park of 400 MW on each location.

Although the site locations used in the ECN study itself are slightly different from the site locations used in the model, the cost-map of the North Sea included in the study is useful for a comparison. The map divides the North Sea in intervals using a price comparison between parks, setting the 100% level at the investment cost of the first Dutch park. From this cost-map, the costs for the 58 model-locations can be estimated (using linear extrapolation between the given cost-lines in the map). In this manner, the ECN cost-value is read for the locations used in the model.

The model is run with similar settings to the ECN study: all parks are set to 399 MW and use a 3 MW turbine. One extra park is added to represent the OWEZ wind farm. To negate any effects of cost reductions due to learning by experience as incorporated in the model, all parks should be built at the same time. Therefore the run is set up with 59 Developer agents matching the number of locations in model. These agents will therefore all develop one park at the same time. For all agents a behavioural setting of 4 ('unlimited') is chosen, so all resources are available. The resulting run shows all 59 parks built on all the North Sea locations (including the OWEZ wind farm) at the same time. Most parks have a size of 399 MW, except 7 parks whose surface area is too small for 399 MW installed capacity.

The investment costs in the model results are set relative to the cost of the extra park OWEZ. In figure 8.1, the result of a comparison of the price levels in the model and the ECN study are shown. The parks are sorted by their distance to the coast. The figure shows that although both keep within the same interval of 100 to 170 %, the division is different. The ECN numbers show two lines, while the model varies along one line versus the distance to the coast. All the parks on the higher line in the ECN study are located in the North of the EEZ. An explanation of the difference could be that ECN study does not include harbours in the North, while in the simulation the harbour 'Eemshaven' is included. In fact, a German harbour could also be included, as this part lies close to the German border.

Note that a straight line is not expected for the costs versus the distance to

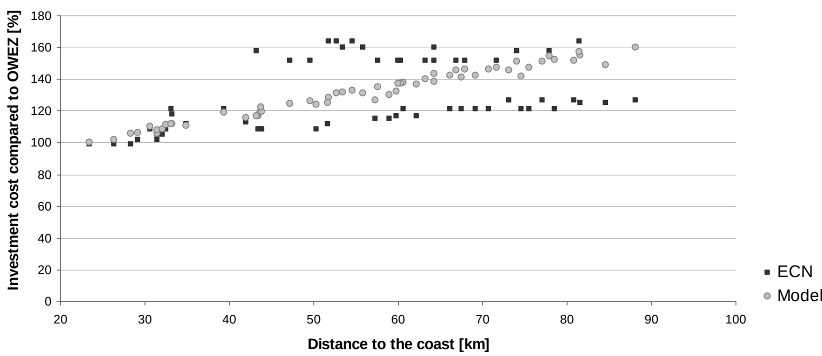


Figure 8.1: Comparison of investment costs from ECN study and model.

the coast. The variation is caused by the effect of the water depth and distances to the harbour and grid. For the different costs of a park, their dependence on water depth and distances have been checked for this model data, and the graphs show an expected form.

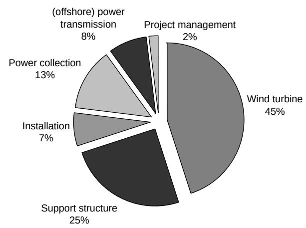
Validation example 2: 300 MW parks

In other studies, the division of costs per part or activity has been estimated. In an Opti-OWECS study [77] an estimation was made of the division of the investment costs and the division of total costs over the lifetime of a park. As a baseline park, the study used a park consisting of one hundred 3MW wind turbines, at a site with an average wind speed of 8.4 m/s at 60m, its central point 15 km off coast near IJmuiden and its water depth at 14-19 m LAT. It is assumed that the decommissioning costs are 10 % of the investment, O&M costs are 9 mln €/year, the wind turbines cost 170 mln € and the assumed interest rate is 5 %.

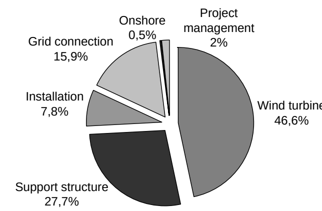
A simulation has been made to compare these results. Since none of the parks in the model are located that close to shore[7], an extra park had to be included for the comparison. However, no specific location is mentioned in the Opti-OWECS study, only that it is close to IJmuiden. The new park in the simulation has been located close to the PAWP. It consists of one hundred 3 MW turbines. The Opti-OWECS study assumed costs for the wind turbines are matched: the base wind turbine price is 566 k€ per rated power and the progress ratio is set to 100 percent to keep this number constant. The other costs assumed in the model have not been changed.

In the figures 8.2 the results are depicted: in figure 8.2(a) the division of the investment costs are given as stated in [77], page 10-1, and in figure 8.2(b) the

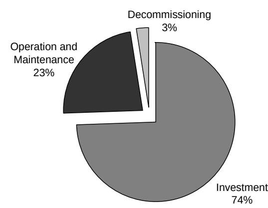
[7] According to regulation, no park will be built within the 12 mile zone except PAWP, whose distance to the coast is about 21 km. In 2013, the door might have been set slightly ajar again for offshore wind farms within the 12 mile zone [275].



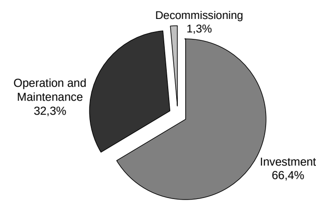
(a) Opti-OWECS investment



(b) Model investment



(c) Opti-OWECS total discounted cost



(d) Model total discounted cost

Figure 8.2: Comparison of the division of costs from Opti-OWECS and the model. The model results have been adapted to fit the categories of Opti-OWECS: the installation of the wind turbines and the foundations, usually in separate categories, are now combined in one category 'installation'.

results of the model for the extra park are given. The main difference between the two are the grid connection cost: 21 percent versus 16 percent. The grid cost in the Opti-OWECS study consists of the power collection (infield cables and the station) and the transmission line, while the grid connection cost in the model consists of the costs of the station and the transmission line, and the onshore work is included in the model as a separate category and the infield cables have not been taken into account. For parks further offshore, the transmission line and station are the major parts of the grid connection investment costs, and the omission of infield cables is less relevant. This park, however, is a large park relatively close to shore, and the infield cables would be relatively more important. So for simulations closer to the shore, the model's underestimation of the grid connection cost will be more prominent. The differences between the other percentages are fairly small.

The discounted total costs division is also examined. Figures 8.2(c) and 8.2(d) give the relative comparison of the investment costs versus the O&M costs. In both pie charts one can see that the investment costs clearly outweigh the O&M and decommissioning costs, but the percentages differ. The Opti-OWECS study assumes O&M costs of 9 mln €/year, while in the model the cost per year would come down to about 15.8 mln €/year. In another study

[61], the O&M costs for Dutch parks have been estimated as 23 €/MWh, and the Opti-OWECS price equals about 8.5 €/MWh. For this study, the O&M costs as estimated by the EWEA in [72] at 15 €/MWh will be maintained.

Note that only for comparison have the costs of wind turbines been matched to the assumptions in the Opti-OWECS study, to be able to compare the percentages. Prices for wind turbines have risen considerably since 1999 when the Opti-OWECS study was performed, due to e.g. high steel prices and high demand. In the simulations to be presented in the next section, the start costs for wind turbines are set to 900 k€/MW. In the sensitivity analysis this wind turbine cost, as well as the O&M costs, will be varied.

8.3 Model results

8.3.1 Model runs using the environmental scenarios

After the verification and validation, the model can be run for analysis. To give an idea of what variations can be analysed using the model, the model settings and its output will be shown here. For this, four different runs are made, based on the four scenarios mentioned in chapter 7. As a reminder for the main axis for the scenarios, figure 7.14 is repeated in this chapter in figure 8.3. Apart from these four different environmental scenarios, the runs also have different behaviour types defined for the agents (different behaviour types) to show a variety of possible settings for possible development paths that can be simulated by the model. The run using scenario 1 for the environmental parameters will be named scenario run 1, etc.

It should be noted that due to the status of the model these runs are not presented to make judgements on e.g. governmental policy or innovation choices. These runs are presented to help showcase the model, particularly to show how modelling different environmental scenarios can affect the implementation by comparing the runs and how explanations and limiting factors of a single run can be found using alternative runs.

Before the results of the four runs are presented, the basic input and output parameters are explained.

Input parameters

Certain input parameters do not vary over the following four simulation runs: the most important of these general input parameters are presented in table 8.3. The scenario-dependent parameters have been assigned a value chosen specifically for each scenario. These scenario-dependent variables include the chosen behaviour types for the agents: risk averse (1), risk seeking (2), or the default (0). In table 8.4 one can find the chosen behaviour types for the most relevant agents; all other agents are given the default behaviour type '0'. Another

Table 8.3: General input parameters

Parameter	Value	Dimension
Maximum power density	7.0	$[MW/km_2]$
Discount factor	7	[%]
Nr of time steps	180	$[ticks]$
Length time step	1	$[month]$

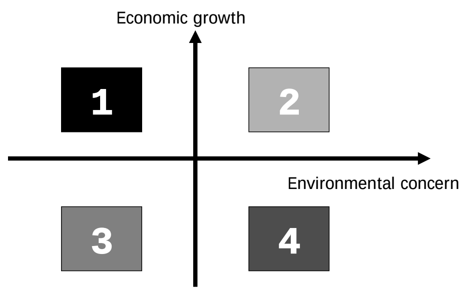


Figure 8.3: The two chosen axis and resulting four scenarios.

example of scenario-dependent input parameters are the progress ratios for the different parts of the park, these are given in table 8.5. Other scenario-dependent input parameters have already been discussed and presented in chapter 7, e.g. the steel price, electricity price, and the installed capacities of onshore and off-shore wind turbines.

Output parameters

To compare the runs made using these four scenarios, certain output parameters are selected as the key indicators, as described in chapter 4. The first group of output parameters concerns the total installed capacity at the end of the simulation. The second group of indicators consists of the costs: investment costs, the expected total costs and the income. As a third group, the characteristics of the built parks are collected. The fourth and last group specifies some results

Table 8.4: Chosen behaviour types for four agent types in each scenario: risk averse (1) or risk-seeking (2).

Agent	Scenario	1	2	3	4
Developer Agent		1	2	1	2
Main Contractor		2	2	1	1
Utility		1	2	1	2
Wind Turbine Supplier		2	2	1	1

Table 8.5: The progress ratios in each scenario per part or activity.

Parameter	Scenario	1	2	3	4
PR wind turbines		0.85	0.85	0.95	0.90
PR substation		0.90	0.90	1.0	1.0
PR cable installation		0.90	0.90	1.0	1.0
PR wind turbine installation		0.90	0.90	1.0	1.0

for specific agents.

The total installed capacity or installed power is the main indicator. For each scenario, one wants to see if the goal of 6000 MW is achieved. In all scenarios, the subsidy office does not give out new subsidies once the 6000 MW has been surpassed: therefore the installed capacities in all runs will never run far past the 6000 MW. For some perspective, the total generated and expected generated power output in TWh is also collected as output.

The costs of the investment will be presented as a total and per installed capacity, the latter having higher comparative strength for the scenario runs. The income of the Developers are the income from the Power Purchase Agreements and the received subsidy. To compare, these incomes are divided by the generated total power output. To compare the total costs of the parks in the different scenario runs, the Levelised Production Cost (LPC) is calculated for each park, and an average LPC is presented for each scenario. The LPC is a measure of the cost of energy and can be compared to results of cost studies. The following equation has been used to calculate the LPC:

$$LPC = \frac{C_{inv}}{a \cdot E_y} + \frac{TOM}{E_y} \tag{8.1}$$

$$a = \frac{1}{r} \cdot (1 - \frac{1}{(1+r)^n}) \tag{8.2}$$

$$TOM = TOM_{annual} + TOM_{oneOff} \tag{8.3}$$

$$TOM_{annual} = \frac{1}{a} \cdot \sum_{t=1}^{n} OM_y \cdot \frac{1}{(1+r)^t} \tag{8.4}$$

$$TOMoneOff = \frac{C_{decom}}{(1+r)^n \cdot a} \tag{8.5}$$

Junginger (as stated in [96]) calculated an expected reduced levelised production cost of 42-54 €/MWh for 2020. Because of rising cost prices, the UKERC 2010 study [96] states that investment costs have gone up from about 1.5 mln £/MW to about 3 mln £/MW (around 1.7 - 3.4 mln €/MW), increasing the LPC from 85 £/MWh to 150 £ (96 - 170 €/MWh), but that cost reductions are expected in the future.

The characteristics for each built park are: the average installed capacity of the park, the average rated power of the used turbines, the average time to go from initiative to a constructed park (named the development time), and the average distances of the locations to shore, grid and selected harbour. The locations of the built parks can be found in a map generated by the model.

For the wind turbine supplier agent, the average occupancy of its wind turbine factory is presented as the average over all agenda entries of the total number of sold turbines divided by the capacity. For the Developer, his successes and failures in achieving permits, subsidies and construction tenders are stated. A park failure refers to a park failed at any point in the planning, e.g. not achieving a permit or a construction tender, while a tender failure represents only the number of times a Developer had an unsuccessful construction tender procedure, due to various reasons e.g. the unavailability of wind turbines for the in the tender stated time for construction. As a last result the number of created connections to offshore grid stations built by the National grid operator are given in the table.

8.3.2 Results of the four scenario runs

For the four scenario runs, the above described indicators are summarised in table 8.6. A more graphic description of the scenario runs is given by the included figures: the map of locations , showing where parks are built, can be found in figures 8.4(a) - 8.4(d); the implementation speed is shown in figures 8.5(a) - 8.5(d); and the average division of investment costs can be found in figures 8.6(a) - 8.6(d).

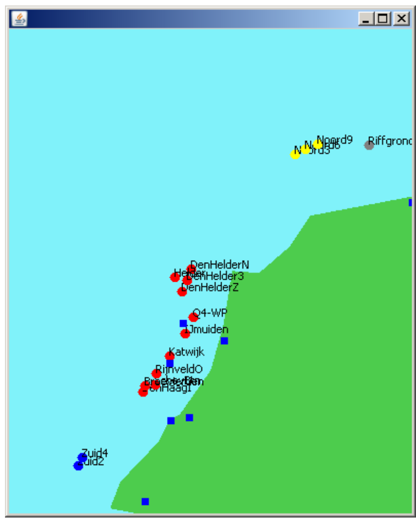
For each run, a short description of the results is given below, which focuses on the relatively high or low numbers in table 8.6 compared to the other scenario runs. Possible explanations for these differences are given and may be investigated using alternative runs. In these alternative runs a certain parameter is changed to investigate its influence on the results. Also, alternative runs may be presented to show how the model can be used for other analyses.

Scenario 1

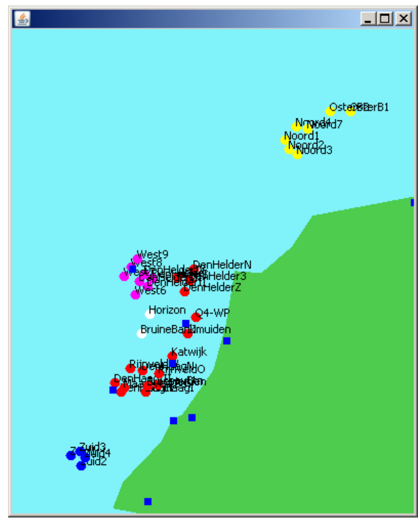
High economic development - Low environmental concern
In the simulation run using scenario 1 the 6000 MW goal is not achieved: less than half that capacity is installed. The implementation starts around midway the simulation time and continues at a fairly even pace. The slightly slower and later implementation does lead to the largest average wind turbine rated power and the lowest investment costs per installed capacity, leading to the lowest LPC. This is because the later development can take advantage of international

Table 8.6: The main results of the scenario runs.

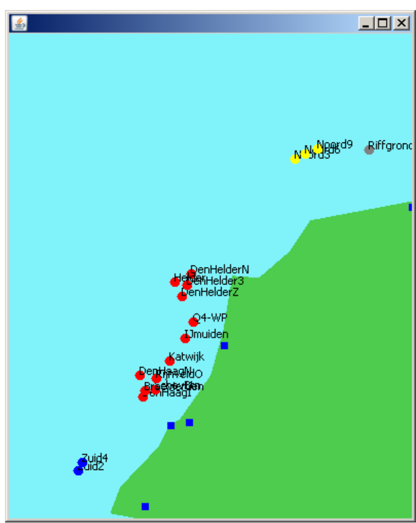
Scenario		1	2	3	4
Total installed capacity	*[MW]*	2680	6216	2410	4710
Total generated output	*[TWh]*	39	108	28	44
Total expected output	*[TWh]*	188	436	169	330
Planned power	*[MW]*	200	0	600	900
Total costs construction	*[mln €]*	5222	14109	5498	11286
Total discounted costs construction	*[mln €]*	3092	8955	3030	6062
Expected costs operation	*[mln €]*	2891	6618	2602	5042
Discounted exp. operation costs	*[mln €]*	805	1936	679	1260
Expected costs decommissioning	*[mln €]*	241	619	242	488
Discounted exp. decom. costs	*[mln €]*	31	87	30	58
Total costs	*[mln €]*	8354	21347	8342	16816
Discounted total costs	*[mln €]*	3928	10978	3738	7380
Total investment costs per MW	*[mln €/MW]*	1,95	2,27	2,28	2,40
Total costs per MW	*[mln €/MW]*	3,12	3,43	3,46	3,57
Total discounted costs per MW	*[mln €/MW]*	1,47	1,77	1,55	1,57
Average LPC	*[€/MWh]*	68	77	75	80
Income PPA	*[mln €]*	1233	4205	662	1575
Discounted income PPA	*[mln €]*	567	1924	290	685
Income PPA per MWh	*[€/MWh]*	32	39	24	36
Income subsidy	*[mln €]*	2512	7192	1484	2036
Discounted income subsidy	*[mln €]*	1186	3318	653	895
Income subsidy per MWh	*[€/MWh]*	65	66	53	47
Total subsidy awarded	*[bln €]*	75	176	91	161
Total income per MWh	*[€/MWh]*	97	105	77	83
Total nr of parks	*[nr]*	17	37	18	27
Total nr of wind turbines	*[nr]*	367	1055	368	687
Average wt size	*[MW]*	7,3	5,9	6,6	6,9
Average park size	*[MW]*	158	168	134	174
Average development time	*[months]*	113	101	128	125
Average distance to coast	*[km]*	35	50	36	51
Average distance to harbour	*[km]*	51	61	51	62
Average distance to grid	*[km]*	65	78	64	80
Average occupancy wt factory	*[%]*	0,075	0,168	0,184	0,283
Permits denied	*[nr]*	8	19	4	15
Subsidies denied	*[nr]*	0	2	0	7
Parks failed	*[nr]*	20	42	14	55
Tenders failed	*[nr]*	16	63	43	60
Postponements	*[nr]*	12	252	46	382
Offshore stations	*[nr]*	2	2	2	2
Offshore grid connection	*[nr]*	1	2	0	0



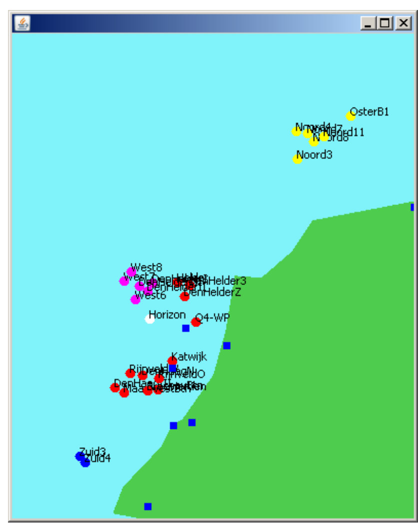
(a) Scenario 1



(b) Scenario 2

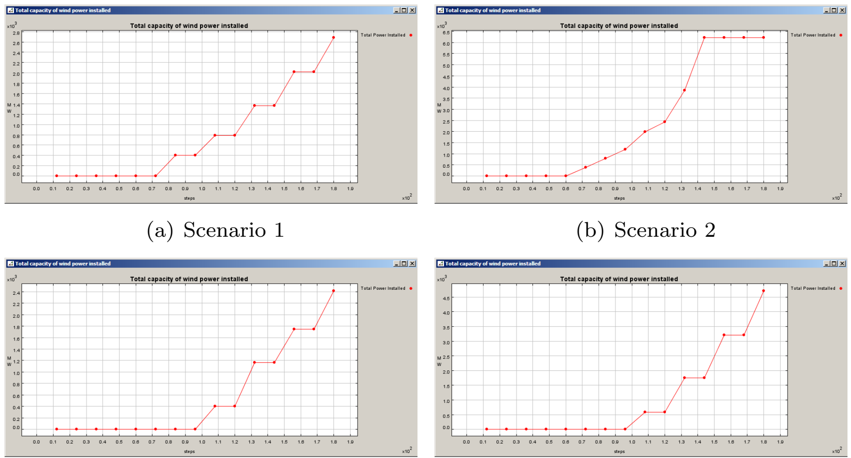


(c) Scenario 3



(d) Scenario 4

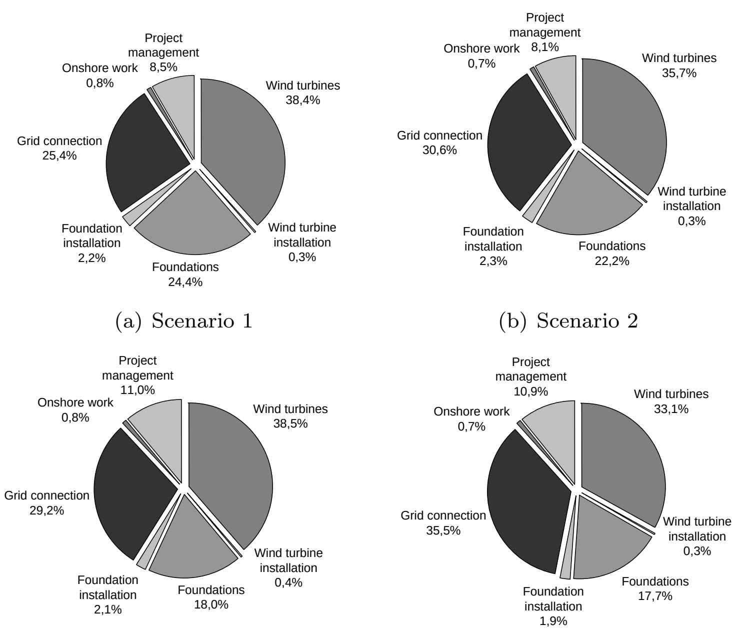
Figure 8.4: The map of locations for the four scenario runs. The round dots are the locations, the squares represent HV station on- and offshore. The different colours of the locations represent the different clusters.



(a) Scenario 1 (b) Scenario 2

(c) Scenario 3 (d) Scenario 4

Figure 8.5: Total installed capacity during simulation for the four scenarios.



(a) Scenario 1 (b) Scenario 2

(c) Scenario 3 (d) Scenario 4

Figure 8.6: Average division of investment costs per part for each scenario.

experience reducing the prices, but also because the locations that are used for parks are all locations fairly close to shore, harbour and grid. The relatively short average distance to the grid also shows in the relatively low percentage of the grid connection in the investment costs. For a higher installed power, also locations further offshore would be required.

The selected maximum subsidy amount Developers can ask for in their subsidy tenders is 0.15 €per kWh of produced electricity. When this maximum is increased, the installed power does not increase: it is not a limiting factor. Lowering this amount does reduce the installed power, however. Here it will be checked when the subsidy becomes too low for any parks to be realised by the Developers by running alternative runs using scenario 1 as environmental scenario. In one such an alternative run for scenario 1, the maximum subsidy amount is lowered to 0.115 €/kWh: only 4 parks are built, totaling to an installed power of 384 MW. All four are built in the last year of the simulation: at this point the prices have lowered enough for parks to become interesting for Developers for the selected maximum subsidy. Since demand then suddenly peaks, the limiting factor becomes the wind turbine manufacturers, as they do not have enough capacity to supply turbines for more than 4 parks (leading to the postponement of four other parks). At a maximum subsidy amount of 0.11 €/kWh, no parks are built within the simulation time.

A higher electricity price may also be thought to lead to an earlier date for implementation, however remember that in scenario 1 a market-based subsidy is given: an electricity price higher than the base price will decrease the subsidy amount per produced kWh (see the explanation in chapter 4, section 4.1.1 on market based subsidies). The extra received price in the Power Purchase Agreements (PPAs) with the utilities has to weigh against this diminished subsidy amount.

In the scenario run, the Developer was chosen to be risk averse: he is considered 'less enthusiastic' due to the low environmental concern in this scenario. One can interpret this as the Developer being concerned about risk, e.g. the technical and regulatory risk surrounding parks. The Developers will then work on a more limited amount of parks at the same time. When an alternative run is made where the Developers' behaviour type is set to risk seeking, a different picture emerges: the total implemented power rises to 6264 MW and the average LPC becomes 78,7 €/MWh. The risk-averse attitude of the Developers is therefore limiting in this scenario run.

The wind turbine factories of the wind turbine suppliers have a low occupancy compared to the other scenarios. The factory capacity was set as a percentage of overall (international) demand, as explained in chapter 6. Since overall international growth is high (leading to a higher availability of turbines as suppliers adjust their factory capacities to meet demand) and Dutch demand is low, the occupancy numbers are low. Still, the construction tenders that fail,

fail because of an unavailability of wind turbines. This is also due to the subsidies being given out in tender rounds (every two years), leading to Developers requesting turbines at the same time.

Scenario 2

High economic development - High environmental concern
This scenario run has the highest implementation of the compared four scenario runs and this time the 6000 MW goal is achieved. The subsidyOffice closes for new subsidies after the 6000 MW has been surpassed, and more parks are not built because at the end of the simulation time offshore wind is not yet economically viable without subsidies.

Since more locations are built in this scenario, the average distances to coast, harbour and grid are relatively high. This has its effect on the division of investment costs; the grid connection costs (the costs for the transmission cables and offshore station) are relatively high. The average LPC is high compared to scenario run 1 because of the earlier start and longer average distances. The selected high technological progress (translated to lower progress ratios) and the strong international wind turbine markets lower the LPC and the LPC therefore stays relatively in check with scenario runs 3 and 4.

The high amount of failed parks are due to the unavailability of wind turbines and the amount of denied permits, as more locations are denied due to environmental concerns or budgetary reasons. Since in this scenario environmental concern is high, certain areas have been excluded for offshore wind park siting. The unavailability of turbines is caused by the Developers' enthusiasm, which causes a high demand in a relatively short time interval. When the Developers' preferred park size is increased from 100 to 300 MW for the first park (keeping the same growth factor) in an alternative run (2A, see table 8.7), the total installed power goes down: increasing the park size also increases this high demand in a short time interval. More postponements and even cancellations of parks are the end result in this alternative.

The high installed power at a fairly high implementation speed leads to a high generated output at the end of the simulation time. The amount of subsidy per produced MWh is however also relatively high. The subsidy amount per kWh is now constant over the entire simulation, but in this scenario the technological progress lowers prices faster than the increased distances for parks can increase them. This is shown in alternative run 2B, see table 8.7. In 2B, the subsidy amount starts at the same value (0.097 €/kWh) but decreases linearly to zero €/kWh in the last simulation year. Since the subsidy is attained before construction of the park, one should not expect the subsidy amount of a park starting operation at time t to receive the kWh amount the subsidy office assigns for new requests at time t. Therefore the prolonged implementation does

Table 8.7: Scenario 2 and its alternative 2A, with a higher preferred start park size, and 2B, where the subsidy amount decreases linearly.

Scenario		2	2A	2B
Installed power	*[MW]*	6216	2943	6049
Preferred park size at start	*[MW]*	100	300	100
Subsidy per MWh	*[€/MWh]*	66	66	48
Average LPC	*[€/MWh]*	77	75	76

not mean that offshore wind is economically viable at the end of the simulation time. The last park in 2B is built in tick 144 (year 12) at a subsidy amount of 0.058 €/kWh.

Two parks are connected to an offshore station: park DenHelderI with an installed power of 175 MW (in year 10, at tick 127) and DenHelderII of 175 MW (at tick 128). The Developers had already designed their park, but redesigned it just before procurement with the new offshore connection when it was announced. If an alternative run is made with no offshore stations being realised within the simulation time, the investment costs for the parks rise: see table 8.8 for the DenHelderIII park. The question remains whether the saved investment costs for the two parks weigh against the costs of the offshore grid station. Also, the two parks are not even that close to the station, but the (slightly) shorter offshore distance to be covered and the cancelled cost of an offshore station makes it interesting for the Developer anyway. If the national grid operator would be able to communicate with the Developers about the possible locations, it could schedule its offshore grid locations according to necessity, whilst now it performs a preordained plan.

The other offshore stations are built after the Developer of the last subsidised park has finished the tendering for the construction, and the contracts after procurement are considered fixed. Before procurement, it is assumed that redesign changes can be made for a park: they are assumed to be allowed in the permit and subsidy without requiring resubmission of requests. In other words, the subsidy and permit are considered flexible for innovation. Had they not, no parks would be connected to an offshore station. Note that in reality such changes to a permit or subsidy bring a risk of losing the permit or subsidy.

When all offshore grid stations are already available at the beginning of the simulation, the reduced investment costs are almost 550 million euro. Each offshore station then has four connections except one which has two connected parks. Scenario 2 has a fixed kWh amount subsidy in the First-Come-First-Serve procedure, so the total subsidy does not go down. The model does not take into account a reduced subsidy for parks connected to the national offshore grid. In this scenario the subsidy amount is a fixed amount each simulated year, and the parks connected to the national offshore grid receive the same subsidy

Table 8.8: Installed power and cost division of park 'DenHelderII' in scenario run 2 and its alternative 2c; no offshore grid stations.

Scenario		2	2C
Installed power of the park	*[MW]*	175	175
Investment costs	*[mln €]*	356	378
Percentage grid connection of inv. costs	*[€/MWh]*	30.3	34.1
LPC park	*[€/MWh]*	70.6	74.1

as parks that have to pay their own connection.

Individual transformer stations have not been taken not account. However, if the distance to the TSO offshore station is far, transformers will be required to raise the voltage of the cable from farm to TSO station; usually 33 kV voltage is used within the farm. The Developer may need to build a transformer station. The costs for an offshore substation has been estimated here only very roughly.

Scenario 3

Low economic development - Low environmental concern
Compared to scenario 2, scenario 3 is at the other end of the scenario axes scales: a low economic development and low environmental concern. It is not surprising that this is the scenario with the lowest implementation: 2410 MW of installed offshore wind power.

Compared to scenario run 2, scenario run 3 has similar investment costs per installed power and the LPC is even slightly lower, even though the cost reductions are lower (the chosen progress ratios are higher) and the internationally installed offshore capacity moves slower. Two reasons can be given. First, scenario run 3 has less built parks and therefore only has a lower average distance to coast, grid and harbour for these parks, as can be seen from the average distances in table 8.6. Second, scenario 3 has lower steel prices.

This effect of lower steel prices can be seen in the comparison to scenario run 1. This latter run has a similar installed capacity and comparable distances for its realised locations. However, the percentage of the investment cost going to the foundations is 24.4 % in scenario run 1 and in scenario 3 this is only 18.0 %, leading to an average foundation cost of 0.48 and 0.41 million €per MW respectively. The effect of the steel price is tested in alternative scenario 3A, where the steel price is set equal to the high steel price in scenarios 1 and 2. The change is significant: the total installed power at the end of the simulation time is drastically lower. The first parks are not built until simulation year 12 or, in real-world terms, in 2017. The investment cost per installed power increases.

Table 8.9: Scenario run3 compared to alternative 3A, where the steel price is high.

Scenario		3	3A
Installed power	*[MW]*	2410	192
Generated power output	*[MWh]*	27.9	1,85
Investment costs per MW	*[mln €/MW]*	2.28	2.43
LPC	*[€/MWh]*	75,0	78,4

In table 8.9 the largest differences between run 3 and 3A are summarised.

To achieve the 6000 MW target, further lowering the steel price has no effect in this scenario: the installed power remains the same. The slow build-up of offshore wind parks is more due to the risk-averse attitudes of the agents.

Scenario 4

Low economic development - High environmental concern
Scenario run 4 does not reach the 6000 MW target, but does come closer than scenario runs 1 and 3. The results for this run show a fairly low subsidy per MWh, but increasing the subsidy amount does not help increase the implementation: in itself, the maximum subsidy amount is high enough for a higher implementation. Instead, the high investment costs per installed power is examined. When looking at the percentages of the different costs in the investment, the high grid connection cost stands out: it is the highest percentage of the four scenario runs. The average distances of the installed parks are similar to scenario run 2, but the latter has a higher installed power and therefore higher distances would be expected. The high number of postponements is investigated as a possible reason for these high average distances in scenario run 4.

When following some locations closer to shore in the trace, they do appear in the plans of the Developers in scenario run 4 as potential park locations. The Developers are very eager, requesting construction tenders for several parks at the same time, but this is too much for the (less enthusiastic) turbine suppliers. The TurbineSuppliers can not match the high demand. After postponement and a second failed tender, some of the parks still have no successful construction tender and are cancelled. The Developers do not receive the information why a MainContractor does not respond to the tender invite: this is taken as limited information about the contracting with the MainContractor. A second failed tender leads to cancellation, and the Developers switch to their other options: parks further away from the coast and the grid. This switch can be seen in the map of park locations and in the average distances and construction costs. The parks' average distance to the coast and grid are the highest of the four scenarios, and the percentage of construction costs for the grid connection is 35.5 % of the total construction costs, much higher than in the other scenarios.

Table 8.10: Two alternatives for scenario run 4 are run: 4A, where the behaviour type of the wind turbine supplier is set to '1'; and 4B, where the allowed lapse time between achieving the subsidy and the start of construction is set to 10 years instead of 5 years.

Scenario		4	4A	4B
Installed power	*[MW]*	4710	6156	1756
Generated power output	*[MWh]*	44	86	15
Investment costs per MW	*[mln €/MW]*	2.40	2.31	2.38
LPC	*[€/MWh]*	80	77	81
Average distance to grid	*[€/MWh]*	80	77	78
Average percentage grid connection	*[€/MWh]*	35.5	32.5	35.9
Postponements	*[€/MWh]*	382		431

Two alternative scenarios of scenario 4 have been run to show the effect of the eagerness and the cancellations, see table 8.10 for a short summary of the results. In alternative 4A, the behaviour type of the turbine supplier is changed to type 2 (risk-seeking). In this alternative scenario the installed capacity rises to 6156 MW at the end of the simulation, a considerable difference to the 4710 MW before. The implementation is realised at lower investment costs, leading to a lower LPC. The average distance to grid has decreased, and the percentage of the grid connection in the investment costs has also decreased. The number of postponements has decreased.

In alternative 4B, the allowed lapse time between achieving the subsidy and starting the actual construction of the park has been changed from five to ten years, to try to lower the amount of cancelled parks. However, this does not have the desired effect: the total installed power decreases (see table 8.10). Also, making Developers less eager does not increase the implementation, it is decreased because the implementation speed is now slower.

8.4 Sensitivity analysis

8.4.1 Set-up of the sensitivity analysis

In the previous section, already some alternatives were shown for the scenario runs by changing certain parameters. In this section, a sensitivity analysis will be presented to assess the effect of the variation of certain parameters. In the sensitivity analysis, parameters will be adapted one-at-a-time (OAT sensitivity analysis) to examine if the model is very susceptible to one particular parameter. This is the easiest way to test the model's sensitivity to a parameter, as the simulation results show the consequences of only this parameter change.

In the sensitivity analysis, a variety of parameters will be selected, defining technological, economical and socio-institutional settings in the model. The chosen parameters describing technological settings are the progress ratios of the wind turbine, installation and station supply. The chosen parameters describing the economical settings refer to the prices of electricity and steel, and the initial costs of the wind turbine per rated power (the cost of the first produced wind turbine: the C_0 in the experience curve calculation described in e.g. [120]). The chosen socio-institutional settings are the procedures for the permit and subsidy, the (maximum) subsidy amount, maximum permitted installed power per cluster, the portfolio obligations for the utilities, and the decision to build an offshore grid.

Apart from these technological, economical and socio-institutional settings, certain simulation parameters are also examined in the sensitivity analysis: the number of Developers and number of wind turbine suppliers (wts) in the simulation. Changing the behaviour types has already shown to have a great effect in the description of some of the scenario runs.

In the previously presented alternatives in the description of the scenario runs in the previous section, only the results of a single simulation were shown as a run of the scenario. To adapt parameters stepwise (using several values), batch runs can be used to shorten simulation time. In a batch run the model is run using a parameter file that specifies an interval and an increment for selected parameters. In a single push of the button the data of several simulations using these different parameters is gathered in one output file. In this run the Repast Graphical User Interface (GUI) and the output to the screen are disabled and the run is therefore considerably faster. These batch runs have been used here for two purposes. First, batch runs have been made with 100 times the same parameters for each scenario to check for instabilities. For all four scenario runs, the batch run result show the same results for installed power and costs. Since the scenario runs do not use random numbers, this is the result that is expected. Second, it is used for incremental parameter changing for the sensitivity analysis.

In part 1 of the sensitivity analysis, economical, technological and simulation settings will be addressed, and in part 2 socio-institutional variations are shown. The results will be examined using the following output parameters: the installed capacity, as this is a major target for this model, the investment costs (per MW) and the LPC as cost indicators and the total required subsidy and subsidy income per MWh.

8.4.2 Results of the sensitivity analysis part 1

An overview of the selected sensitivity analysis parameters in part 1 are given in table 8.11. Each batch run is presented in four graphs, one for each run using an environmental scenario. The graphs of the results of the batch runs can be found in appendix E. These graphs are all of similar form: the x-axis gives the values of the parameter under investigation, and the y-axis gives the installed power, investment cost per installed power, given subsidy per generated MWh

Table 8.11: A short description of the parameters and their variations in the batch runs of the first part of the sensitivity analysis.

Batch	parameter changed	dimension	lowest	highest	increment
1	PR wind turbine	[-]	0.80	0.98	0.02
2	PR grid connection	[-]	0.80	0.98	0.02
3	O&M cost	[€/MWh]	15	23	1
4	wt start cost	[mln €/MW]	0.6	1.4	0.1
5	Electricity price	[€/kWh]	0.03	0.09	0.01
6	Steel price	[€/tonnes]	0.9	1.8	0.1
7	Nr Developers	[-]	2	10	1
8	Nr turbine suppliers	[-]	2	10	1

and the LPC respectively. The four outputs are presented as a percentage of the original value given in the table of the scenario runs.

Wind turbine progress ratio

Increasing the wind turbine progress ratio would lower cost reductions, so the investment costs go up. The change in the investment costs is around 20 % for a change of 0.80 to 0.98 for the turbine progress ratios. To check this cost effect, the average decline is examined for a product with a set price of 100 and a progress ratio of 0.8 with the installed capacity of offshore wind as the produced number of items to calculate the cost reductions. At the end of the simulation, the installed capacities for the low, medium and high implementations are 19000, 30000 and 40000 (MW) respectively. The end price is 34.39, 29.69 and 27.06, with an average change of 42 to 46 %[8]. Since the wind turbines make up about 50 percent of the costs, the average change for the investment costs would be about 20 %, assuming the implementation is constant over time. Especially scenario 2 has a faster implementation, which could account for the lower change (around 17 %). The effect of the wind turbine progress ratio on the investment costs seems therefore in order.

When the PR is 0.85, the investment costs are about two-thirds of the LPC, but this ratio varies as the progress ratio and therefore the investment costs change. The increase and decrease of the LPC at lower and higher progress ratios seems in order. The given total subsidy follows the change in investment costs, except in scenario 2 as this scenario has a fixed subsidy. The installed capacities in the scenario runs are not affected by the cost reductions for the wind turbines: this is apparently not a limiting factor in the runs (note that the installed capacity in scenario 2 is still above the 6000 MW).

[8]Given a price of 100 in year 1 and a progress ratio of 0.8, then if someone would build 1 per year, he would pay 34 in year 15 and 58 on average over the 15 year period, hence an average reduction of 42 %.

Note that this unchanged installed capacity for the four scenarios does not mean that the progress ratio can never have an effect on the total installed capacity. When the subsidy amount is assumed to diminish over time, the cost reductions will affect the total installed capacity, as they are then necessary to make the project profitable. In scenario run 2 in section 8.3.2, a linearly decreasing subsidy showed to have a great effect on the total given subsidy without reducing the installed power. In an alternative simulation that has been run to test the effect of combining the linear reduction for the subsidy and a progress ratio of 0.98 (instead of 0.85) for scenario 2, the total installed capacity drops to 2308 MW.

Grid connection progress ratio

In the grid connection progress ratio (PR) actually two parameters are changed: the progress ratio of learning for the offshore station (with and without converter) and for the installation of the cable. In scenarios 1 and 2, these were first set to 0.90. For scenarios 3 and 4, the progress ratios were both set to 1.00 (in other words, no learning effects). In the graphs one can see the expected rising investment costs per MW and the LPC for higher progress ratios. In none of the scenarios it has an effect on the installed power. In scenarios 1, 3, and 4 one can see that the required subsidy goes down as the PR goes down.

In all scenarios, the change in investment costs as the progress ratio moves from 0.90 to 0.98 is about 6-8 percent. Since scenario 4 has the highest percentage of grid connection cost in the investment cost, the largest change can be seen in this scenario. In all graphs one can clearly see the values assumed in the first scenario runs of section 8.3.2. Again, just as for the wind turbine progress ratio, no effect can be seen on the installed capacities.

Wind turbine initial cost

The initial cost of the wind turbine is the price of the first produced unit used in the experience curve. Since this parameter is also very uncertain, the value of the wind turbine initial cost will be varied from 0.6 mln €/MW to 1.4 mln €/MW. This represents a fall of 33 % and rise of 56 % compared to initial value of 0.9 mln €/MW. In scenario 2 and 4 the fixed subsidy and maximum subsidy amount in those scenarios are high enough for the higher wind turbine start cost to have no effect on the installed capacity. In scenarios 1 and 3 the total installed capacity strongly decreases after the start cost rises over 1.0 - 1.1 mln €/MW respectively.

Note that the given subsidy per MWh in the tender based subsidy procedures varies greatly, while again in scenario 2 it remains fixed. The fixed subsidy has the advantage that is more predictable what the expenditures on subsidy would be, as uncertainties such as the wind turbine start cost are not of influence. On the other hand, for lower start costs the Developer agents obtain 'windfall profits' and the subsidy expenditure is not diminished. In the model, the expenditures on the tender-based subsidy are contained by the set maximum amount per MWh and a yearly budget. The tender-based subsidy however has a stronger influence on the installed capacity.

Comparing these results to a previous parameter change, the wind turbine progress ratio, note that the latter had no effect for the installed capacity while changing the initial cost does: this is of course because the change of the initial cost changes the cost already in year 1, while the higher progress ratio gives a slower cost *reduction*. In the changing progress ratio, installed capacity and generated power output is not affected for the chosen changes, while the decreasing installed capacity and faster decreasing output for the higher initial costs of the wind turbine show that implementation is delayed: Developers are waiting for lower costs as in year 1 it is not yet profitable to invest in a park.

O&M cost

The O&M costs are about 35 % of the non-discounted costs, and about 20 percent of the discounted total costs in all four scenarios, therefore a 53 % increase would bring an increase of about 10 % in the LPC, as can be seen in the graphs. As long as the installed capacity remains the same, the investment costs are unaffected. As the change in the O&M costs changes the NPV estimation of the Developers, their investment decision might be negative and their requested subsidy amount will change, leading to a change in installed capacity and given subsidy.

For both high wind turbine initial cost and high O&M cost, only the installed capacities in scenario 1 and scenario 3 are highly reduced. This can be explained by the investment behaviour of the Developers in these scenarios: because of their risk-averse attitude the Net Present Value of the investment has to be positive after 8 investment years instead of 10 years for the more risk seeking Developers in scenarios 2 and 4. Also, the risk averse Developers request a higher profit margin, and the maximum subsidy amount would therefore sooner be insufficient for the risk averse Developers, leading to the decrease in installed capacity. The difference between scenario 1 and 3 could lie in the relatively higher O&M costs in scenario 1.

A batch run with O&M costs up to 40 € per MWh has been run. Two effects of this run has not been explained. First, comparing the variation in the O&M costs to the variation in wind turbine initial cost, one can see that the changes to the O&M costs seems to have a relatively higher impact on the LPC. Second, in scenario 4 the installed capacity goes up when the O&M costs are above 30 €per MWh.

Electricity price

For the market-based subsidies, the basic electricity price is set at 0.06 or 0.066. The input parameter is the base-load electricity price. This base-load electricity price is related to the basic electricity price set for the market-based subsidies, since the electricity price (p_{el}) for wind generated electricity is set as:

$$p_{el} = f_w * f_u * f_p * p_{bl} \tag{8.6}$$

where f_w is the adjustment factor specifically for wind generated electricity set at 0.667, f_u is reduction factor due to the unbalance costs (which are set at 7 %) and is 0.93, f_p is the reduction factor due to the profile costs of wind energy and is 1.0 (all set according to [145]), and p_{bl} is the base-load electricity price. Therefore, if the baseload electricity price is higher than 0.097 or 0.106 respectively, one should see the total subsidy spent start to decline for the scenarios with a market-based subsidy scheme. The interval for the baseload price in the sensitivity analysis is therefore set from 0.03 to 0.15 €/kWh. Note that it is an end price: it is the price for the produced electricity at the end of the simulation. All scenarios start at the 2005 base-load electricity price, but rise or fall to the mentioned input end electricity price.

In the graphs in appendix E one can see that after an electricity price of about 0.09, the received subsidy begins to decline as expected for scenarios 1,3 and 4. The decline in subsidy for scenarios 1, 3 and 4 should match the rise of the end electricity price after 0.09 €/kWh. Indeed the graphs show a decrease in subsidy per produced MWh after 0.09 of about 30 to 40 % as expected, except in scenario 4: in this scenario the drop is larger. The linear decline in the electricity price may explain this. For all electricity prices, the scenarios 1 and 3 both have an installed capacity of around 2500 MW of installed power, while scenario 4 has around 4700 MW. For all four scenarios, the generated output is also about constant in the runs with varying electricity price.

If the assumption is made that the implementation has a similar build-up as seen in the scenario runs in section 8.3.2, the difference in drop for the subsidy could be explained. The implementation in scenario 1 starts slightly sooner than 3 and 4, therefore a higher percentage of its generated power output is generated in the beginning when a higher subsidy amount is still given to parks. Scenario 1 therefore has a slightly higher percentage of subsidy than scenario 3, which ends at the same installed power. Scenario 4 has almost twice the installed power of scenarios 1 and 3, although the generated output is not much higher than the generated output in scenario 1: this means more parks are constructed in the end and they therefore receive a lower subsidy amount per produced MWh.

For scenario 2, the variation in electricity price has no effect on the given subsidy, since the subsidy amount is fixed. For all four scenarios, the electricity price has no effect on the costs (investment cost and LPC) as expected. An effect is expected in the estimated Net Present Value (NPV) and the received

PPA-price for the Developers, but these were unfortunately not included in the selected output parameters. These will be addressed later in this chapter.

Steel price

In scenario runs 1 and 2 in section 8.3.1 high steel prices were selected, while scenario runs 3 and 4 were run with low steel prices. In the sensitivity analysis for the steel price, the steel price is varied between these high and low prices. In scenario 1 and 2, the lower steel prices gives lower investment costs and LPC. Since in scenario 4 the maximum subsidy amount is higher, the total installed capacity remains the same. In scenario 3, however, the steel price becomes too high at a certain point and as the investment costs were already high in this scenario due to e.g. higher progress ratios, the total installed capacity decreases after a steel price of more than 1.3 k€/tonnes.

Number of Developers

The number of Developers in a simulation has a large effect on the installed capacity. In scenarios 1 and 3 the Developers are set to risk averse and the rise in numbers of Developers gives a rise in the total installed capacity, as now a higher implementation speed can be achieved. This increase is gradually developing into a decreasing effect when other agents cannot keep up with the demand of the higher number of Developers, and postponements and cancellations occur.

Scenarios 2 and 4 both have risk seeking Developers and the decrease in total installed capacity already sets in after more than four Developers. This can be explained with the same reasoning as described in scenario run 4 (see 8.3.2) by the occurrence of more postponements and cancellations.

Number of wind turbine suppliers

For this batch run, It should be noted that for each scenario a total capacity for all turbine factories is given and spread over the number of wind turbine suppliers. With more suppliers, the capacity does therefore not increase. In two of the scenarios a large effect on the installed capacity can be seen however. This is because in these scenarios the total factory capacity is lower and the number of suppliers influences the sum of capacities of the wind turbine factories of the suppliers. This is caused by the manner of division of the scenario total capacity: the division is rounded up to the first integer, and especially in the first months where the capacity per supplier's factory could be set to one or two turbines per month, this roundup can make a large difference. This will lead to a higher availability of wind turbines especially in the beginning of the simulation, and this was an issue mentioned in both scenarios in sections 8.3.2 and 8.3.2. The rise in the installed power is therefore a result of more available turbines.

Table 8.12: Overview of the simulations for the second part of the sensitivity analysis.

Run	Change	Run	Change
1a	Subsidy tender	2a	First Come, First Served
1b	High electricity price	2b	All sites permitted
1c	All sites permits	2c	No portfolio obligations
1d	Fast offshore grid	2d	Fast offshore grid

8.4.3 Results of the sensitivity analysis part 2

In this section a number of socio-institutional aspects are examined. These are of a more procedural nature and require more than one parameter change. Because this requires more attention than one parameter, the focus is placed on two scenarios instead of all four: scenarios 1 and 2.

The variations chosen for this part of the sensitivity analysis are the tender rules, the rules for permitting, the portfolio obligations and the offshore grid. Previously it was shown that the type of subsidy procedure has a great influence, therefore a switch will be made: scenario 1 will be run with a fixed subsidy in 1a, and scenario 2 with a subsidy tender in 2a. For scenario 1 a check is made of the electricity price in run 1b, since in part 1 of the sensitivity analysis only the effect of the electricity price in the subsidy amount was regarded, while the PPA income is of importance as well. The effect of excluding certain sites and setting a maximum on the installed capacity per cluster will be examined in alternative runs 1c and 2b. For scenario 2, the effects of the portfolio obligations will be examined in 2c. Both scenarios will be run with a fast implementation of the offshore grid stations (alternatives 1d and 2d). In table 8.12 an overview is given of the alternative runs for this second part of the sensitivity analysis. Here runs instead of batch runs are compared. The results are summarised in tables 8.13 and 8.14.

Alternative 1a and 2a: Running scenario 1 with the fixed, First Come, First Served subsidy gives a higher total capacity. The Developers can take a faster pace in developing their projects as they do not have to wait for the end of a round for a decision on a subsidy request. The implementation therefore shows a more smooth line instead of the step-wise function shown in figure 8.5(b). This one-by-one approach (instead of groups in subsidy tenders) in park development also causes the average park size to go up (179 instead of 158).

Only two more parks are built for the extra 728 MW installed capacity. The total investment costs per MW are lower, mostly due to lower wind turbine costs and lower grid costs[9]. The wind turbine average rated power is higher,

[9] This data is not included in the tables, but is included as output just as in the scenarios runs.

Table 8.13: Second part of the sensitivity analysis: alternatives for scenario 1.

Scenario		1a	1b	1c	1d
Total installed capacity	*[MW]*	3408	2680	3560	2680
Total generated output	*[TWh]*	40,3	38,8	42,7	38,8
Total expected output	*[TWh]*	238,8	187,8	249,5	187,8
Total investment costs	*[mln €/MW]*	1,90	1,95	1,89	1,87
Total costs per MW	*[mln €/MW]*	3,06	3,12	3,05	3,04
Total discounted costs	*[mln €/MW]*	1,35	1,47	1,36	1,41
Average LPC	*[€/MWh]*	66,51	67,90	66,44	64,57
Income PPA per MWh	*[€/MWh]*	32,7	46,1	32,4	31,8
Income subsidy per MWh	*[€/MWh]*	66,4	43,5	62,7	64,7
Total income per MWh	*[€/MWh]*	99,1	89,7	95,1	96,5
Total nr of parks	*[nr]*	19	17	20	17
Total nr of wind turbines	*[nr]*	444	367	456	367
Average wt size	*[MW]*	7,7	7,3	7,8	7,3
Average park size	*[MW]*	179	158	178	158
Average development time	*[months]*	118	113	120	113
Average distance to coast	*[km]*	36,7	35,3	36,6	35,3
Average distance to harbour	*[km]*	52,6	50,9	49,9	50,9
Average distance to grid	*[km]*	65,0	65,3	62,0	44,0
Permits denied	*[nr]*	11	8	0	8
Subsidies denied	*[nr]*	0	0	2	0
Parks failed	*[nr]*	24	20	12	20
Tenders failed	*[nr]*	16	16	36	16
Postponements	*[nr]*	9	6	8	6
Offshore stations	*[nr]*	2	2	2	2
Offshore grid connection	*[nr]*	2	1	1	11

Table 8.14: Second part of the sensitivity analysis: alternatives for scenario 2.

Scenario		2A	2B	2C	2D
Total installed capacity	*[MW]*	6129	5997	6175	6319
Total generated output	*[TWh]*	97,9	109,4	107,0	105,9
Total expected output	*[TWh]*	429,5	420,3	432,7	442,8
Total investment costs per MW	*[mln €/MW]*	2,16	2,36	2,29	2,15
Total costs per MW	*[mln €/MW]*	3,33	3,52	3,45	3,31
Total discounted costs per MW	*[mln €/MW]*	1,62	1,83	1,77	1,66
Average LPC	*[€/MWh]*	75,9	79,1	78,0	72,2
Income PPA per MWh	*[€/MWh]*	41,2	33,6	33,8	34,0
Income subsidy per MWh	*[€/MWh]*	51,8	66,4	66,4	66,4
Total income per MWh	*[€/MWh]*	93,0	100,0	100,3	100,4
Total nr of parks	*[nr]*	37	38	36	36
Total nr of wind turbines	*[nr]*	903	1055	1049	1063
Average wt size	*[MW]*	6,8	5,7	5,9	5,9
Average park size	*[MW]*	166	158	172	176
Average development time	*[months]*	106	102	101	102
Average distance to coast	*[km]*	48,7	52,5	49,1	48,5
Average distance to harbour	*[km]*	60,8	62,0	60,8	60,5
Average distance to grid	*[km]*	76,1	76,3	77,5	52,8
Permits denied	*[nr]*	18	0	20	20
Subsidies denied	*[nr]*	3	20	2	2
Parks failed	*[nr]*	42	40	44	44
Tenders failed	*[nr]*	40	71	64	72
Postponements	*[nr]*	68	126	118	252
Offshore stations	*[nr]*	2	2	2	2
Offshore grid connection	*[nr]*	4	3	2	20

indicating the lower wind turbine cost arises from a later wind turbine choice and the higher cost reductions by (international) experience. The grid costs reduction arises from the now two offshore connection points instead of one. The subsidy amount is about the same as before.

Scenario 2 with a tender-based subsidy also has lower investment costs than before. Here, the reduction mostly comes from cheaper turbines with a higher average rated power. The tenders now calm the pace of the eager Developers in this scenario, and the installed capacity is built a little later than before. This leads to the availability of larger, cheaper turbines as a choice for Developers after they have received their subsidy and two more connections to the offshore grid. The installed capacity is still above 6000 MW, and the 78 MW less installed capacity therefore has no comparative value. The selection of the subsidy tenders instead of a fixed subsidy amount reduces the subsidy, from 66 to 52 €/MWh.

In both scenarios, the subsidy tender gives a lower total given subsidy. The FCFS with a linear reduction for the subsidy as presented in part 1 of the sensitivity analysis still gives a lower spent subsidy per generated output (48 €/MWh): apparently the cost reductions over time outweigh the increased costs due to less optimal sites (i.e. further away from coast, harbour and grid). In both scenarios, it is the combination of the behaviour type of the Developers and the type of subsidy procedure that influences the implementation speed.

Alternative 1b: To check the PPA income, the alternative 1b was run as a scenario 1 run with a higher electricity price. Indeed, the PPA income per MWh is higher. The given subsidy decrease is higher, however, than the PPA price increase: the total income per MWh is lower. In the model, the utilities are not very generous with their PPA prices.

Alternative 1c and 2b: In these alternatives, all sites are acceptable for permitting and no maximum is set for the installed capacity per cluster for both scenario 1 and 2. In 1c, the installed capacity goes up. Three more parks are built in cluster 2, as more capacity is now allowed, see figure 8.7. As now more of the cheaper sites in cluster 2 are available to the Developers, the installation costs per MW go down.

In alternative 2b, the installed capacity unexpectedly seems to go down as total installed capacity is now slightly under 6000 MW. Twenty subsidies are turned down, and checking the trace tells us that all have been turned down because the subsidy office has reached its maximum of 6000 MW. This is because the subsidy is requested using a preliminary park design, before procurement: the constructed park might be a little less because of the selected turbine size and the allowed maximum power in the permit: if a Developer has the permit for 100 MW and selects 3 MW turbines, the constructed park will be 99 MW. The investment costs unexpectedly go up in alternative 2b. This may have to

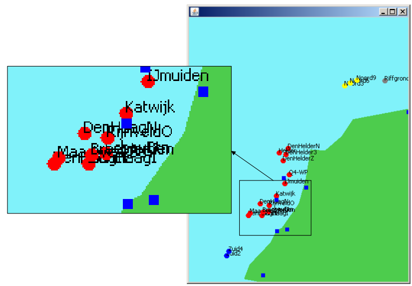


Figure 8.7: Locations of extra parks in alternative 1C.

do with the estimation of the costs of the sites by the Developers, causing them not to always select the actual cheapest option.

Alternative 2c: Cancelling all portfolio obligations does indeed cause the PPA income to go down as expected. The investment costs for the grid connection costs are slightly higher, leading to slightly higher investment costs. Since the distance to the grid is lower, this can not be the reason. A reason may be in the different average park size: the number of cables needed for the grid connection may work disadvantageous in this alternative.

Alternative 1d and 2d: Two alternative runs have been made with a fast implementation of an offshore grid[10] using both scenarios 1 and 2. In both scenarios, the investment costs are lower due to lower costs for the grid connection. In both alternative runs, the distances to the grid were lower than expected. In scenario 1, a fast offshore grid implementation can save 60 million €/GW[11], and in scenario 2 this saving is even 120 million €/GW. A higher total installed capacity gives a higher reduction of the average distance to the grid and therefore a higher reduction of the investment costs. The decision for a national offshore grid is therefore dependent on the envisioned installed capacity. As the costs of the offshore grid have not been included in this study, the overall benefit of an offshore grid (whether the costs weigh against the investment reduction and subsidy reduction) cannot be commented upon.

8.5 Discussion of the results

8.5.1 General goals of the model

In the previous chapters, the components of the model have been described: the agents with their main behavioural aspects, and the environmental scenarios with its main parameters. In this chapter the functioning of the (implementation of the) model has been discussed, to see how these mentioned components

[10]In fact, the implementation goes back in time, as the stations are built in 2006.
[11]1 GW = 1000 MW.

function together during a simulation run. In this study, the simulation model has been created with the intention to analyse the possibilities of such a model. The model results will therefore be examined and discussed by addressing its validity, variability and extensibility, as these are seen as the main goals for the simulation model.

The model's validity addresses how well the model simulates the intended purpose, both in procedural sense and in the sense of the realistic values of results [16]. Its variability addresses the different conditions a model can simulate, by varying input parameters to show what the model can do and different situations can be analysed with model. Its extensibility reflects the amount of effort required to implement extensions to the model for future growth, e.g. to enlarge its scope.

Validity

The validity of the model is addressed by checking the implementation and the realism of the results: the validation and verification of model. The validity will also be ascertained from the results of the scenario runs and the sensitivity analysis in section 8.4.

Using extreme conditions and trace checks, the model has been verified satisfactorily. The execution time of the model is short, which is convenient for checking the model using unit testing, for example to test a new procedure of an agent. Although the entire model could not be compared to other studies due to the integrated approach, specific parts of the model have been compared to other studies for validation. Extreme conditions and specially orchestrated simulations were used to match the assumptions of these other studies. The results of this validation were satisfactory.

The sensitivity analysis has shown that the changes of the chosen model output parameters after variation of one parameter are mostly explainable. However, since one parameter can affect several outputs, explaining changes was sometimes not evident, especially in the second part of the sensitivity analysis, where procedures instead of one parameter were changed. Alternatives were used to check possible explanations. In not all cases of an unexpected result an explanation was found.

The validity of the model is of course dependent on the quality of the gathered data and the chosen scope. Specifically for agent-based modelling, detailed data is required because of the micro-founded modelling approach, instead of more general data that can be used in approaches using a macro-view analysis. There were therefore some difficulties with data gathering due to the confidentiality of detailed data and the fact that the modeller cannot be an expert in all incorporated fields.

Variability

The variability is tested in the different presented runs of the simulation model. These runs showcase different possibilities of use of the model: the different situations it can simulate. The scenario runs and the sensitivity analysis have shown that alternative runs or batch runs can be made to vary certain parameters. The model includes a wide variety of parameters in interaction. This shows that economical, technological and socio-institutional aspects and changes can be incorporated in the agent-based model. In the agent-based model, behavioural aspects can also be incorporated, in a clear and transparent manner. However, describing all the choices and assumptions is a bit tedious.

The scenario runs have shown different results amongst the runs for all possible model output parameters. The interaction of the agents and the parameter changes certainly can be seen in the variety of the results of the scenario runs. Not just parameters have been varied, but also procedures and behaviour types have been varied. The use of scenarios proves useful, as a complete set of parameters and procedures can be varied by only changing one input parameter in a consistent and clear manner.

Extensibility

The extendability is addressed in both the sensitivity analysis and discussion. The latter also discussed the limitations of the model. The model has been implemented step-by-step. At first a small (e.g. three) number of agents was implemented, their procedures and communication lines verified and then the model was extended further by increasing the detail in the behaviour of the agents or adding more types of agents. For the validation, a certain amount of agent types and detailing is required to be included in the simulation model before runs can be made with output that can be validated. In the future, the model can be extended in a similar manner to increase the scope of the model.

The model is therefore certainly extendable. Delineating the model's focus and when to stop extending the model could be even stated as more an issue than the extendability of an agent-based model itself. The model can certainly be extended, and in the chapter 10, some recommendations will be made as to what extensions would be interesting.

8.5.2 Reflection on the results

As time has passed between setting the input values for the key elements and running the simulations, and subsequently describing all results, some inputs can already be seen to suffer from limited information and unforeseen changes. For example, the wind turbine innovation defined in individual installed capacity and wind turbine cost estimations from 2005-2020 have already been shown too optimistic. It should be noted that total accuracy has not been the focus (nor expectation) for this study; the identification of relevant factors and the (possibility of) modelling these factors has been, showing a span of institutional, technological and physical aspects. For all future studies, the difficulty of guesstimates is a factor. For the model to be applied, more data should be gathered: confidentiality of data can be dealt with, in determining what output is presented in what manner to the general public.

The choice has been made to define the input parameters mainly in a high, medium and low value and to select a value for a run according to preselected scenarios. For presentation purposes, scenario planners usually advise not to show more than four distinctive scenarios. This guideline was followed here in this study into the potential of ABM to generate scenarios. Due to its fast calculation time, full factorial sweeps may be possible for ABM. Here, this would lead to a possible 3^{13} (1,594,324) runs, a high number of cases even considering the fast calculation time per single run. It should also be noted that the high, medium and low values most often describe a time series: they represent high, medium and low end values. For 'all possibilities' for the selected input parameters different shapes could also have been taken into account, resulting in even more simulations. This would have resulted in a high number of cases to analyse. The author feels that interesting combinations can still be found (although not all of them) by selecting relevant scenario drivers and reducing the number of scenarios. Selecting the most interesting cases from an enormous amount is also a subjective selection, just as a selection of four scenarios is. Although in the latter case the subjectiveness is higher, the transparency is also higher: it is more clear to the stakeholders how choices for runs have been made.

In the presented simulations, a single run was sufficient as no random numbers have been used. It was deemed that the study did not profit from randomising certain parameters because it would no longer be possible to assess the effects of certain choices. In retrospect, one element could have profited from a random approach: the sequencing of the agents. E.g. because 'DeveloperAgent1' always moves first he always gets first pick. Randomising the sequence would have excluded such first-mover effects.

9

Conclusions

Introduction

The aim of this study is to examine if a model can be used to identify the barriers and opportunities to the implementation of large-scale offshore wind energy in the Netherlands, taking into account the uncertainties of the future and consequences of decisions, from technological, economical, social, political and environmental perspectives, towards a 6000 MW target by 2020. The research question was stated as to investigate whether an agent-based model could provide such a method by the simulation of implementation paths. An agent-based model has been developed to simulate implementation paths towards 6000 MW installed offshore wind power in the Dutch EEZ. In this chapter the research question and the subquestions will be addressed, by addressing the suitability to the overall approach, the chosen methodology and the conclusions on the model. The main advantages and disadvantages are summarised.

9.1 Conclusions on the approach

9.1.1 The research question

The research question has been defined as: can an agent-based model be used to develop realistic implementation paths towards 6000 MW installed offshore wind power in the Dutch EEZ that show the consequences these paths entail for the stakeholders? In chapter 2, the view on such implementation paths has been described. In the subsequent chapters, the development and results of the agent-based model have been described, and the conclusions on the model and methodology have been given, but how well does the approach of an agent-based simulation model fit with the original outset?

It was described that the agent-based model has to simulate a socio-technical system, which is a multi-actor system, and an implementation path is seen as

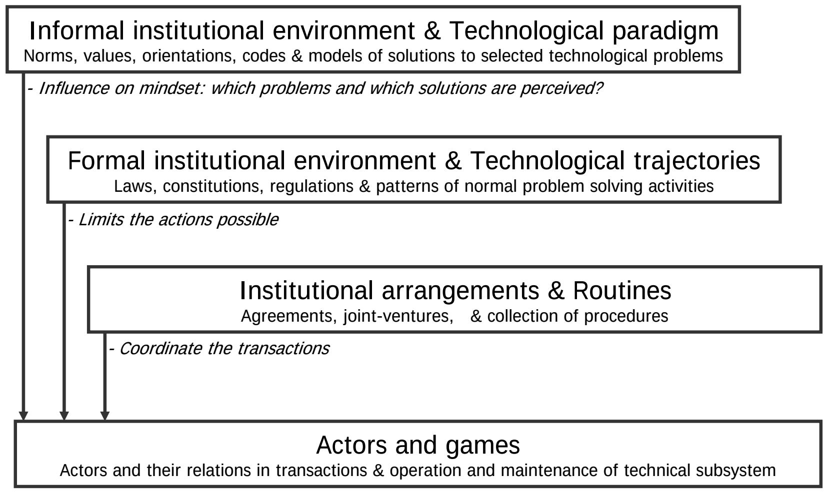


Figure 9.1: Framework for this study, repeated from 2.1.

a co-evolution of both technology and institutions. This evolutionary process is viewed as micro-founded by the actions of these multiple actors. Four levels of institutional analysis and technological practice were presented, with different purpose of change and frequencies of change. The actions of the actors are part of the fourth level and these actions are constrained by the three levels above it. In figure 9.1, the framework showing the four levels is repeated for ease. It will be discussed how well the model has captured these founding aspects.

A micro-founded, multi-actor system

Agent-based modelling was chosen because it was believed to be able to simulate a multi-actor model. The resulting model does indeed represent a multi-actor system by including several types of heterogenous agents. The (dynamics of this) system can be seen as micro-founded by the actions of the agents, as the implementation paths are built up by the actions of the interacting agents, each serving their own interests, representing the stakeholders in their relevant, differentiated roles. The approach is concluded to be suitable to simulate a multi-actor model, but with the following side-notes.

A limit has to be set to the number of actors represented in the model by the agents; certain stakeholders have therefore been neglected. Environmental scenarios have instead been defined, for a variation of the environment of the agents. This environment can be seen as including the actions of actors that have not been included as agents (e.g. law makers, electricity traders). All changes for the environmental scenarios have been dictated for each simulation in the environmental scenarios. This is considered a suitable approach because the model can represent the focus of the study, and the variety in the environmental scenarios can depict the different changes impacting on the focus agents while keeping the model a manageable size. For example, all actors trading on the electricity market have not been included, instead an electricity price is set as an environmental input.

Agent-based modelling has the advantage of as-is modelling: the elements in the model are recognisable as real world elements. In modelling the agents, one can therefore look at the real world actors to determine protocols and attributes for the agents. It still has to deal with the disadvantage that actors' interactions in real life are multiple and complex. In their representations in the model, all the strategies and interactions of the actors have been simplified. For example, the developer chooses a site based on a simplified NPV calculation, but it does not take into account e.g. possible preferences on locations. Modelling bounded rationality has been incorporated by limiting what information the agent can see and receive and by including routines and protocols for agent behaviour.

In all models, the assumptions are guiding in interpreting the results; here the modelled, simplified behaviour of actors are part of the model assumptions. The conclusion is therefore that this approach is suitable to create a demarcated, simplified model of a multi-actor system.

A socio-technical system

The agent-based model can simulate a socio-technical system, where technological and institutional elements are combined. The results show that it is possible to include a variety of elements in this approach to simulate the socio-technical system the implementation of offshore wind is a part of, in the manner described in figure 9.1. In the delineation a variety of topics was chosen of both technological and socio-institutional nature. The model shows that, both in the agents and their environment, this variety of elements can be seen and their mutual influence are shown in the results.

The elements are related to all four identified levels for technological practice and institutional analysis. The implementation paths are built up by the actions of the agents in an agent-based simulation, representing the Level 4 actors and their games in the day-to-day operation and management and allocation of their resources. Such actions are for instance the park operator collecting the production-based subsidy. In the simulation model, the interactions of the agents follow defined routines and protocols: their transactions are guided by certain rules and procedures. This represents level 3, where the technological practice is arranged according to routines and the institutional arrangements shape and constrain the actions by coordinating the transactions along certain protocols. E.g. the Developers follow a certain procedure or protocol in the decision to invest in a new park. The investment decisions of other market parties influence the Developers' decision (availability of resources) and methods are used for the decision making such as the calculation of the Net Present Value.

In the development of the (inter-)actions of the agents and the environmental scenarios, it has been taken into account that the actions of the agents are shaped and constrained by informal and formal institutions, and the technological paradigm and socio-technical trajectory (level 1 and 2). For instance, the development of the wind turbines is assumed to develop along a dominant design, and the permit procedure is shaped by laws (e.g. Administrative Law[1], tendering).

Co-evolution

The agent-based modelling approach is only partly suitable for the simulation of the co-evolution in socio-technical implementation paths. For co-evolution, all levels for a socio-technical system are to be incorporated to find the elements of these levels evolve, influencing, shaping and constraining each other.

In the developed model, the actions (level 4) of agents within an environment create the implementation paths, and the agents adapt in time, but they do not *evolve* from a simple to a more complex form. The developments on level 1-3 are not evolving within the model either: they are not influenced by the agents. Instead they are prescribed, as explained above, to demarcate the system. As stated in figure 9.1, the influence of the level 1-3 on level 4 are considered, but not the other way around.

Incorporating possible changes to Level 1 and 2 in these environmental scenarios for comparative runs is considered a suitable approach, as the chosen time horizon justifies a more 'fixed' approach for levels 1 and 2. Changes on level 1 are considered revolutionary changes that are not included in the scope. Because the actual present status of level 1 and Level 2 can be hard to ascertain, they are incorporated using several environmental scenarios in a simulation run. For one single simulation, this results in technological development progressing in accordance to one dominant design, and informal and formal institutions remaining unchanged. The 15 year time horizon and the varied, consistent view offered in the scenarios is considered to justify not adding an influence of the agents on laws, regulations or technological trajectories, with all its theoretical uncertainties.

On level 3, one might want to see changes in the arrangements for an evolutionary path within the 15 year time horizon. But this requires implementing many protocols and identifying the conditions on which agents switch protocols. In this study, this is considered outside of the scope: rather this could be investigated in an experimental setup with homogenous agents testing different protocols. Here protocols fitting within the environmental scenarios have been used, for a consistent choice and a more general view. This approach does not offer the possibility to test the performance of several protocols, let alone deter-

[1] Algemene Wet Bestuursrecht

mine when to switch to another protocol.

The difficulty lies in modelling complex actor behaviour. The practical limit to the actual micro-founded aspect has already been discussed: there are simply too many possibilities to include. In the implementation of such changes the same goes as for the incorporation of behaviour: one can try to include complicated behaviour, but ease of as-is modelling does not help anymore at a certain point. For the higher levels, a wider scope and smarter agents are needed to come to completely new arrangements. But to implement them, one would have to know how to define the behaviour of these smarter agents and how their actions influence the upper levels. This is a field of study in itself. Experimental setups or serious gaming may shed light on further, complex actor behaviour, but for this study this is not the chosen focus.

In this model, adding possible developments of the socio-technical system by developing different environmental scenarios, prescribed protocols and adapting (not evolving) agents has been considered a satisfactory approach to attain very different implementation paths in which the influence of different aspects can be shown.

9.2 Conclusions on the methodology

9.2.1 Methodology phases

The conclusions on the methodology are presented, divided over the four identified phases, see figure 9.2, the graphic representation of the methodology from chapter 3 (repeated here for ease).

9.2.2 Analysis phase

The analysis phase has been an essential part of the development of the model, as it led to a demarcation for the model. This focus determines what is to be included in the model and in what detail. Although agent-based modelling is receiving quite some attention, there is not much work published on agent-based modelling methodologies and a description of a specific analysis phase is often missing in the ones that are described. In this study, some methods and instruments are suggested and used. However, although methods and instruments are available to perform such an analysis in a structured manner, it should be noted that such methods and instruments often have a large subjective component.

An actor/factor analysis was performed to delineate the study using literature, a Group Decision Room (GDR) meeting and interviews with stakeholders. Interviews are always powerful as one can gather information from experts, and the GDR offered the opportunity to gather information from several experts at once and get to some consensus on which elements should be included in a

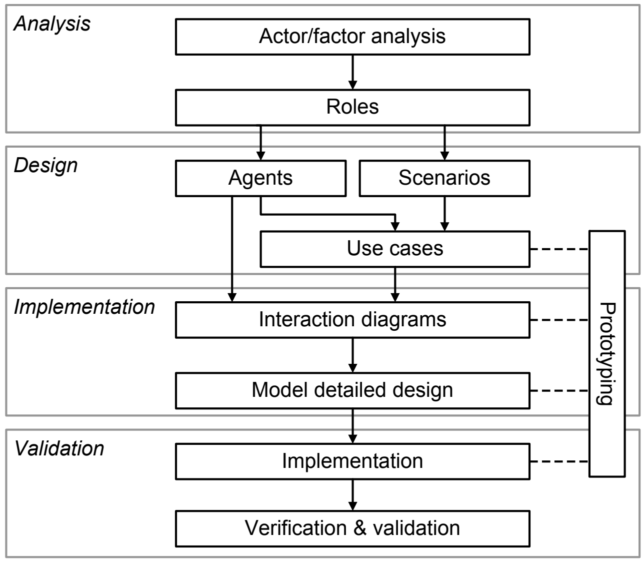


Figure 9.2: The steps of the methodology.

model. Although no new topics arose from the GDR, the perspectives on and ranking of these topics by different stakeholders were clarified.

The scenario planning step plan proved useful to prescribe consistent stories for the environment with a broad variety in topics. The focus from the delineation and model requirements determined the choice for the relevant agents and the elements for the environment of these agents. Using scenario planning, thirteen key elements have been identified and 4 environmental scenarios have been described. The variation in the key elements over these four fields show that a span of institutional, technological and physical aspects are addressed in the environmental scenarios as desired for the background of the model.

9.2.3 Design phase

The role-based approach chosen for the model development (instead of an actor-based approach) is a suitable approach for creating implementation paths on a general overview level, as a micro-analysis *into specific firms* is excluded. It should be noted that micro-level assumptions on actor behaviour still need to be translated to agent behaviour. The effect of a variety of actor's attitudes has been shown by defining several behaviour types (e.g. risk averse, risk seeking).

Use cases and interaction diagrams have proven useful. Interaction diagrams are helpful in collecting the basic procedures to be implemented for agents. Even though the resulting interaction diagrams are representative for the implementation of the model, many sub-methods (and their difficulties) were still unforeseen in the initial design.

9.2.4 Implementation phase

An agent-based modelling approach is not a fast method. While during the design the advantage of the as-is modelling of agent-based modelling made it easier to decide where to incorporate certain elements, the actual implementation takes considerable time. A large amount of data was required to fill in the model. Specifically for agent-based modelling, certain detailed data is required because of the micro-founded modelling approach, instead of more general data that can be used in approaches using a macro-view analysis. This includes behavioural aspects as described above, but also detailed information on e.g. pricing. The specific need for such detailed information was often not clear until far into the design or implementation of the model. The development of the model was therefore an iterative process, as one often has to switch back to analysis or design, to gather data using extra interviews and literature, prototyping and redesign of certain procedures.

9.2.5 Validation and verification phase

The results of the validation and verification are considered satisfactory using existing techniques for validation and verification of simulation models. In general, testing the validity of agent-based models can be difficult because of low comparability to other studies and the complexity.

While during the implementation static testing methods have been used such as trace checking, dynamic testing has proven most useful for testing the validity of the model. Although the entire model could not be compared to other studies due to the integrated approach, dynamic testing proved useful to validate parts of the model one at a time. Extreme conditions and specially orchestrated simulations were used to match the assumptions of these other studies to create data that has been compared to these studies. For verification, unit testing and runs with extreme conditions proved useful to find bugs in specific implemented procedures.

The disadvantage of complexity did show in explaining unexpected results. The sensitivity analysis has shown that the changes of the chosen model output parameters after variation of one parameter are mostly explainable. However, since one parameter can affect several outputs, explaining changes was sometimes not evident, especially in the second part of the sensitivity analysis, where procedures instead of one parameter were changed. Alternatives were used to check possible explanations. In not all cases of an unexpected result an explanation was found: this can be a lack in explaining power, or an undiscovered bug.

9.3 Conclusions on the model results

The developed simulation model has been used to create several implementation paths based on the four environmental scenarios and several alternative runs to check certain parameters. In creating implementation paths using the agent-based simulation model, certain positive and negative things must be remarked upon.

The model meets the general goals set here for the agent-based simulation model: validity, variability and extensibility. The model includes a wide variety of behavioural, economical, technological and socio-institutional parameters. The model's extensibility already became clear during the implementation of the model, as agents can be added one at a time.

The different runs show the influence of different types of input on the main output parameters. The model output makes it possible to compare several scenario runs: e.g. the implementation speed of offshore wind, the overall cost and cost division, subsidy and PPA income, characteristics of built parks such as distance to coast, permit and subsidy procedure results and offshore grid connections. The results of the model show that the model is capable to show the influence of the availability of resources on the overall implementation speed, as a reduced availability leads to postponement or even cancellation of parks. For example, the availability of wind turbines proved limiting in some of the described runs. It has also been shown that in alternative runs, the model output can be used to explain the effects and changes on the implementation speed.

It has been shown that the simulations can present the consequences for different (types of) stakeholders. The selected behaviour types for the agents have been shown to influence the model output, including the resulting costs and incomes for several agents e.g. the Developer Agent. In the four different scenarios, different results are shown for the costs, income and average characteristics of the park.

However, as this is the simulation of the complex system, there is no complete overview of the simulation. The number of agents, the degree of variety in the agents and the behavioural aspects of the agents complicate this overview. The results of a simulation emerge from the separate actions of the agents. In some cases this led to unexpected results or a surprising combinations of output parameters. For these cases, alternative runs have been used to find explanations. By varying one parameter in such an alternative, one can see the effect of one change in the hope of attaining some insight in the original run. However, scenario run 4 showed that even with the use of these alternative runs an explanation of the results was not found.

The model is better suited for comparative costing than cost estimations. Certain assumptions and simplifications had to be made for the model, which restrict what can be deduced from the model. The presented costs in the model are comparative costs, to be used for comparison of runs, as certain costs have been left out, e.g. the cost of capital or the costs of insurance; or simplified, e.g. the operational costs are solely based on an estimation of the yearly O&M costs. Future estimations of costs are 'guestimates'. For example, the innovation of the wind turbines is included in the model by learning curves for the cost development, the rated power estimations and steel price, the latter two both dependent on the technological progress of the environmental scenario. However, recent years have not shown a decline in wind turbine costs, which can not be explained by rising steel prices.

The model is better suited to be used to find limiting factors and influences of parameters than to create implementation paths towards 6000 MW in each environmental scenario. In only one of the four main scenario runs the target of 6000 MW is achieved by 2020. The reasons for not attaining the target most often lie in the timing: e.g. the government permit or subsidy procedures can cluster demand of the developers and therefore harm the availability of wind turbines. In some alternatives 6000 MW was achieved by relieving some limiting factors. This shows that limiting factors can be found within the implementation paths. However, changing chosen parameters incorporates a loss in consistency for the run. It is better to use this model to find limiting factors than to use it to tweak and tune until 6000 MW is the end result: this also lies in the challenge of the ambitious target.

As the model results always depend on its assumptions, it should be noted that situations leading to fully predictable results have not been included for the four scenario runs[2]. For example: including the situation 'no subsidy is available' will of course lead to 'no parks are built', but this does not demonstrate the possibilities of the model, even though up to 2013 this is still the case.

9.4 Main advantages and disadvantages

Agent-based models can be useful in simulating different future implementation paths. They provide a suitable method for examining barriers and opportunities in future implementation of a technology by examining the limiting factors in simulations. The implementation paths are simulated *towards* a target of large-scale implementation, even though the target itself has not been achieved in all paths. The agents represent the different perspectives on the change in the socio-technical system. Their decision making is affected by the other agents and their environment, and changing their behaviour profile (affecting their decision making) impacts the implementation.

Whereas many other methods that take into account both the development of institutions and technology are descriptive ex-post analyses, or are purely

[2]The fully predictable situations have been used in the verification.

qualitative, subjective methods, agent-based modelling offers a method for possible future developments using both qualitative and quantitative data. Both socio-institutional and technical elements can be included in the model to represent the elements of the socio-technical system. The implementation paths thus simulated are created by the actions of the agents, fitting with the idea of micro-foundedness by the actions of the actors.

The constraints on the agents (informal and formal institutions, technological paradigm and technological trajectory, institutional arrangements and methods in technological practice) can be incorporated in the model, as the agents follow certain interaction protocols for their transactions and are constrained by their environment. This environment can be used to represent the informal and formal institutions, and the technological paradigm and trajectory and can be varied by using several internally consistent environmental scenarios.

A critical note is the practical limit to what can be incorporated and how, and this affects the suitability of the approach. This especially concerns the realism of the implementation of human behaviour, which is much more adaptive and complex in real life than can be described or foreseen. To create a co-evolving model, difficulties arise with which protocols to include and when agents should switch. The combination with methods such as serious gaming where input is given during the simulation from actors directly could perhaps be profitable.

The results showed that the effects of changing variables or procedures on the implementation speed and the consequences for other agents can be made visible. By incorporating different types of agents in a changing environment, a variety of aspects can be taken into account in the model. A general level model is easier and faster, but ABM offers a nice way to form different paths of implementation to show consequences of decisions on the overall implementation speed, taking into account behaviour, resource levels, investments, technological development, and institutional aspects. The use of model is more suitable for "insight not numbers" examination, where implementation paths are generated for comparison, due to the difficulty or data gathering and behavioural descriptions.

Summarising, the main advantages and disadvantages of using agent-based modelling are:

The main advantages

- *The model combines technological and socio-institutional elements.* The model shows how technological and socio-institutional aspects can be combined by the inclusion of interacting heterogenous agents in a changing environment. The resulting output of the model describes an implementation path as a dynamic time path. Different input settings can be used in a simulation run to assess their effect.

- *The model combines qualitative and quantitative data.* Agents can be programmed to deal with both quantitative and qualitative information. Note that the manner in which agents respond to qualitative data is interpreted to quantities, as this remains a computer model.
- *The ease of as-is modelling.* The elements in the model are recognisable as real world elements. In deciding what procedure should be located where, one can think back at which actor would have that responsibility in the real world. The inclusion of different behaviour types makes varying the agents' behaviour for the simulations easier and can model a variety of behaviours.
- *The model is easily extendable.* The model was built up agent-by-agent. The model can be extended in a similar manner, whether one wants to widen the scope (e.g. to include a new agent) or include more detailed behaviour (making an existing agent more complex).
- *A model is transparent.* An agent-based model could provide more information on interrelations and provide a greater transparency of the model than more (qualitative) approaches which rely solely on the creativity of the modeller. It does still suffer from a certain amount of subjectivity, for instance in scope choice and chosen input parameters.

The main disadvantages

- *The model requires a certain 'mass'.* One needs to incorporate a certain amount of content in the model before the socio-technical system under investigation is modelled and can be simulated: a selection of agents and environmental input parameters need to be present. Although experimental theory testing can be done in smaller, more abstract models (using homogeneous agents), simulating a socio-technical system requires a certain amount of (heterogenous) agents. As the model grows larger, the explanation of all included parameters and protocols becomes more tedious.
- *Capturing behaviour and change.* Capturing the behaviour in a model has its limits. For a part, bounded rationality can be captured as agents are modelled to follow protocols and routines. But one can not escape the fact that a human is a complex reasoner.
- *Data gathering is extensive.* Other approaches such as scenario planning to examine future development for a certain technology are often macro-level studies requiring more general data. The chosen micro-founded modelling requires more detailed information from a variety of fields (e.g. wind energy technology, the energy market, governmental policy).

10

Recommendations for future research

10.1 Recommendations for the model

10.1.1 Expansion of scope

For this study the model has been given a certain scope of topics to be included. This scope could be expanded and certain topics could be included in further detail for future simulations.

The first issue to address is the role of vessels in the model. As stated in the extensibility of the model, only the (un-)availability of wind turbines can now limit the implementation as a resource. Vessels might play an important role however and may prove a limiting resource. The required adaptation of vessels or investment in new vessels could prove to be of high importance. More specific characteristics can be given to the vessels, to include operational capabilities and outdating of vessels. For example, larger turbines can affect the installation time for a turbine installation vessel as the number of turbines that can be transported diminishes or the dimensions of the components of larger turbines can necessitate new vessels. A balance may have to be struck between the investment cost and time in a new vessel versus the wind turbine cost. This level of detail is not currently incorporated in the model.

It should be noted that the agent type `windTurbineInstallationAgent` is already included with its resource: an installation vessel with a booking agenda. A renewed installation vessel can be given operational capabilities such as deck space or crane capacity. A main contractor can book this vessel from the installation agent for a park for the specific months he plans to have the turbines ready for installation. In determining the number of required months, the installation agent can take into account the number and dimensions of the wind turbines. Weather windows can be included that increase the total number of days it would take to install a certain number of turbines. Current Dutch regulation excludes certain months for construction of the parks because migration and breeding. Such exclusion months could be incorporated in the assessment of the required number of months for the installation.

Second, the turbine market model now consists of an international market and a fixed percentage of each turbine factory as available for the Netherlands. This market could be included in more detail for instance by including the German and the British demand on project basis. An extensive project database then needs to be incorporated of future projects, combined with market expectations.

Third, the required harbour space is currently not limited in the model and is only calculated for the wind turbines, but also the foundations will need to be stored at the harbour before installation. Especially for large parks, limited suitable harbour space at certain harbours could make certain harbours unsuitable or prolong the installation time.

Fourth, the impact on the environment and other users of the North Sea has been included in this study by the (im-)possibility and the runtime of achieving a permit for certain locations. With further knowledge on the environmental impact of offshore wind parks and detailed maps of sea life habitats and movements, cumulative environmental impact of several offshore wind parks can be included. The cumulative effects of offshore wind parks on each each other can be included if such effects have been mapped, for instance by calculation of the reduced yield due other parks in the proximity in combination with the wind rose.

Other aspects that may be incorporated are the inclusion of vertical integration as the propensity for agents (roles) to work together, as certain governance structures for industries could reduce transaction costs in contracting; and the inclusion of an electricity market model, e.g. by adding electricity trader agents, as this can improve estimated consumer prices and power purchase agreements production prices.

10.1.2 Costs

Certain costs aspects in the model can be refined: the following suggestions are made in order of importance.

The operational costs are now solely the O&M costs. These O&M costs are a fixed amount per MWh, while including the distances of the park to coast and harbour is prudent. The operational costs therefore need more attention.

The infield cables have now been excluded: their costs should be included in the model. A basic configuration can be used for all wind farms, dependent on the number of turbines and the power density.

At present, no costs are calculated for the construction of an offshore grid. A comparison whether the costs of a station are outweighed by the savings of the Developers in the grid connection are therefore not made here. The expected savings can be used to lower the received subsidies for parks connected to the 'national offshore grid': this aspect is currently not included in the model and the savings are therefore purely for the Developers of those parks in the simulation.

Other aspects that could be included are the capital costs or the costs of an insurance, the foundation dependence on wind speed and soil properties, and the dismantling costs. To include soil properties and wind speeds in the foundation weight estimation, a GIS could be used instead of the linearised map. The dismantling costs is set to always make out 3 percent of the non-discounted costs. Instead, this could be set according to the (future) installation costs.

10.1.3 Behaviour

In the model it was assumed that developers have limited information on why tenders might not have been successful, leading to cancelled parks. This needs refinement. The developer makes an initial cost estimate based on the costs for foundations, wind turbines, offshore cables and the offshore station. The exact design can change however, at which point the developer again calculates the Net Present Value for the investment. Especially for subsidy tenders this estimation is of importance and this procedure could be refined. One aspect in the NPV estimation that needs to be incorporated is the estimation of the energy yield based on the mean wind speed of the site: this information is already available for the locations, but the developer uses a fixed capacity factor for the estimation of energy yield at present in the model.

The behavioural types of the agents have shown to have a large effect on implementation and costs. More information on the expected behaviour would be very valuable, which could be gathered through more interviews or real gaming.

10.2 Recommendations for the methodology

In this study a methodology has been suggested for agent-based model development, as there are few relevant methodologies and most do not include an analysis phase that identifies what should be modelled. Attention should be given to fitting methods and instruments for such an analysis phase. A few changes will be recommended here for the methodology used in this study. In figure 10.1, a revised scheme for the methodology is depicted.

One change refers to analysis and design during implementation and validation and verification to take into account that data gathering and design are not serial processes. The option to have an analyst creating a picture of the system and identify the focus and issues and a model developer for the modelling itself and the implementation could be profitable, because full advantage can then be made of the different competencies of an analyst and a modeller. After the identification of the elements of the model, the analyst could work in parallel with the developer as one gathers the required detailed data and the other starts the implementation of the model.

As a second change, the modelling could benefit from a more participatory approach, continuing after the analysis phase. Cooperation from experts is desirable to include elements in higher detail. A cooperative process could therefore be beneficial. This could improve the modelling of the behaviour of the agents considering their procedures and their (limited) information and create ownership to the results. This latter aspect is especially relevant if the resulting scenario runs are to be used for policy or decision support amongst a group of stakeholders. A participatory route could be achieved by included stakeholders in a study in an advisory board, by periodic Group Decision Room meetings or by use of the Delphi method [48].

Standards are required especially tuned to the requirements of an agent-based model. Methods for validation and verification would be of great value to modellers, as validation and verification of an agent-based model can be tricky due to emergent behaviour and comparability.

10.3 Recommendations for the approach

Further development of agent-based modelling could provide further, universally applicable tools. The extension of existing toolkits[1] focussed on socio-technical system simulation would make implementation and validation of an agent-based model faster in future, especially for agent-based models including many heterogeneous agents. In programming, standard routines for messaging, input scenarios, and batch runs input files can be included or made easier. In validation, standards for relevant dynamic testing techniques can be gathered. The development of the model can be performed by a group of persons or a combination of an analyst and a model designer & programmer, also for the participatory route.

In chapter 2, several advantages of rational modelling techniques for socio-technical systems were stated: it pushes a modeller to consider an issue from several actor perspectives, it gives insight in the known and unknown variables;

[1] Or the development of a new toolkit.

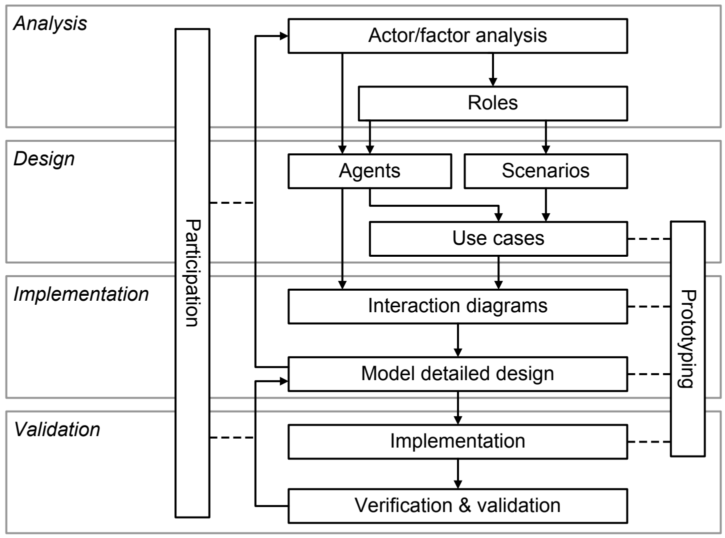


Figure 10.1: Suggested changes to steps for methodology.

and the 'modelled actor network can facilitate the discussion and decision making' [104]. The latter, to test if the approach can facilitate discussion and decision making, has not been investigated here. This would however be an interesting followup.

Appendix A

Repast J Agent based model

A.1 The basic shape

The basic shape of a Repast ABm consist of at least the following three Object classes: the `Model`, `Space`, and `Agent`. The `Model` is the main file that handles the first initiation of the `Space` and the agents; it builds up the simulation model and adds agents to an environment. During the run, it schedules the actions of the agents by addressing their method `step()`. Using this method `step()`, agents can register their actions in the schedule [175]. The `Space` forms the Environment, the outside world of the agents that influences (and is influenced by) the agents. This can be a 2D grid that remembers the positions of the agents or a more abstract world of input data for the agents. The agents are placed in this `Space`. A simulation model has only one instance of class `Model` and one instance of class `Space`, but many instances of class `Agent`. Furthermore, one can have a single class of `Agent` (homogenous agents) or several classes as several different objects.

To give a better idea of the basic shape of a Repast model, simple examples of these three classes with only rudimentary methods are given in figure A.1, in Java code. In an object-oriented language such as Java, all objects initiated are of a certain class or type of Object, and classes can inherit methods (functions or procedures) from other classes as a parent-child or this case class-subclass relation (the `extends` code).

The main is the initiating class and therefore includes a `main` method where the model starts. Agents are added to the instance space of class `Space`. In the method `buildSchedule` of the class `Model`, `StartModelStep` is coded as a subclass of the Repast class `BasicAction`. This Repast Object can be scheduled by Repast. In this example the `StartModelStep` is scheduled as an ac-

```
Public class Model{

...

public void setup(){...}

public void begin(){
        buildModel();
        buildSchedule();
        ...
}

private static void main(){
       SimInit init            = new SimInit();
       OweSimModel model       = new OweSimModel();
        init.loadModel(model, "", false);}

public void buildModel(){
        addAgents();

}

public void buildSchedule(){

        class StartModelStep extends BasicAction {
                public void execute(){
                        for(int i=0;i< agentList.size();i++){
                                Agent agent = agentList.get(i);
                                Agent.step();
                }       }
        }
       schedule.scheduleActionBeginning(0, new StartModelStep());
       ...
}


}//EndOfClassModel
```

```
public class Space {
…
      public void
      addAgent(Agent agent){
       agent.setSpace(this);
      }

}\\EndOfClassSpace
```

```
public class Agent {
…
      public void step(){
       agentAction();
      }

}\\EndOfClassAgent
```

Figure A.1: The three basic Objects in a Repast model: the Model, the Agent and the Space.

tion at the beginning of each Tick by calling on the Repast `schedule` method `scheduleActionAtBeginning()`. A Tick is a time step in Repast Java schedule. By coding these subclasses of `BasicAction` and placing them in the schedule by the method-call, the schedule arranges which Tick which agents are active, in a random order. The agents in the `agentList` therefore perform their `step()` at random order, for instance they could look around, make a step forward and request something from another agent.

A.2 Comment on thread-based versus tick-based

Some might argue that Repast is not fully agent-based because the agents react on the ticks of a main controller, the main file 'Model'. However, when dealing with large populations and/or many time ticks, the thread-based agents will follow through their steps at different speeds, as they have to wait to be allotted execution time. This can lead to great discrepancies between agents' activities, as usually the allocation of execution time is not evenly divided. A simple example program made in Java can show this. One hundred agents are instantiated in one hundred threads, and their objective is to count to one thousand. By the time the first agents have finished their count, some agents can be seen to still be counting below 950. The agents will therefore need to be tied to some kind of communal clock to be given 'a fair share'. Repast solved this by letting the main file 'tell the time' to the agents.

Appendix B

Project schedules of six cases

B.1 Explanation

Of all six cases described in chapter 5, project structures have been made. The structure shows the name of the park in a shadowed box on top, followed by the owner and/or developer of the park. In the next boxes, contracting is shown: the top box hires a connected box underneath it. The name of the actor is shown in bold, the activity of the actor is shown in normal text.

B.2 Project structures

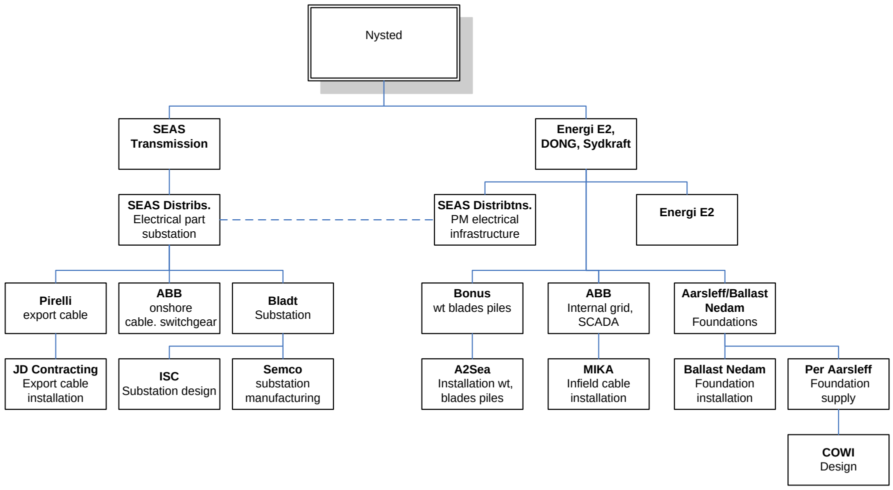


Figure B.1: Nysted project schedule, Denmark

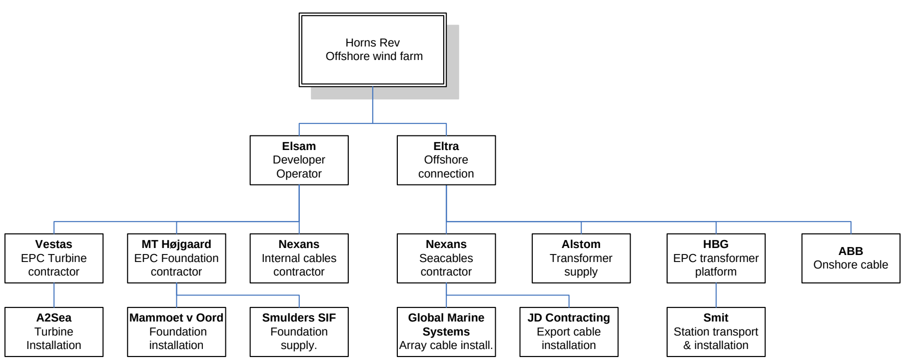


Figure B.2: Horns Rev project schedule, Denmark

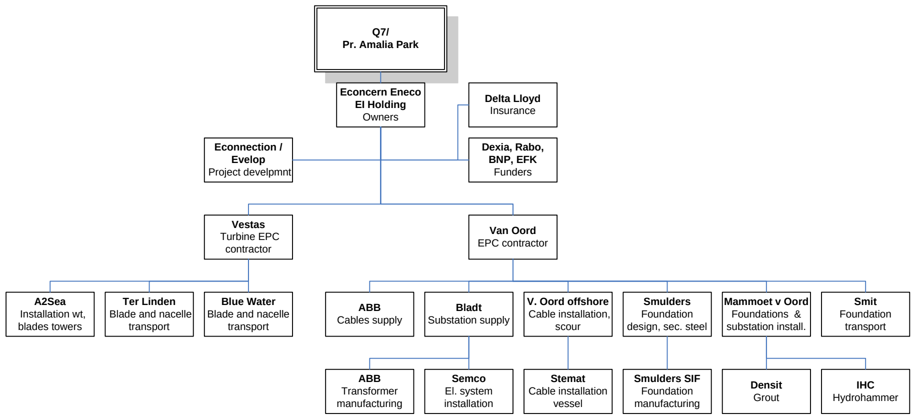


Figure B.3: Q7 project schedule, the Netherlands

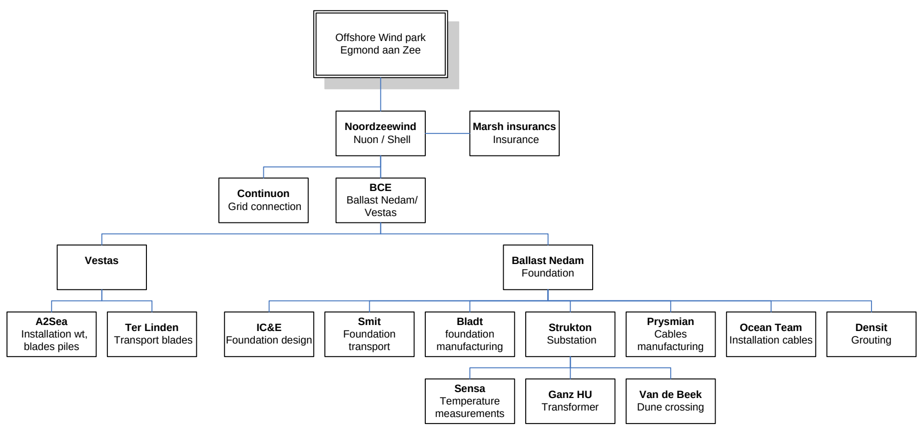


Figure B.4: OWEZ project schedule, the Netherlands

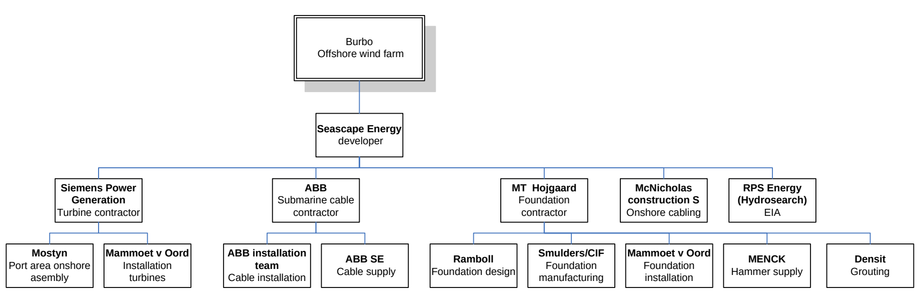


Figure B.5: Burbo project schedule, United Kingdom

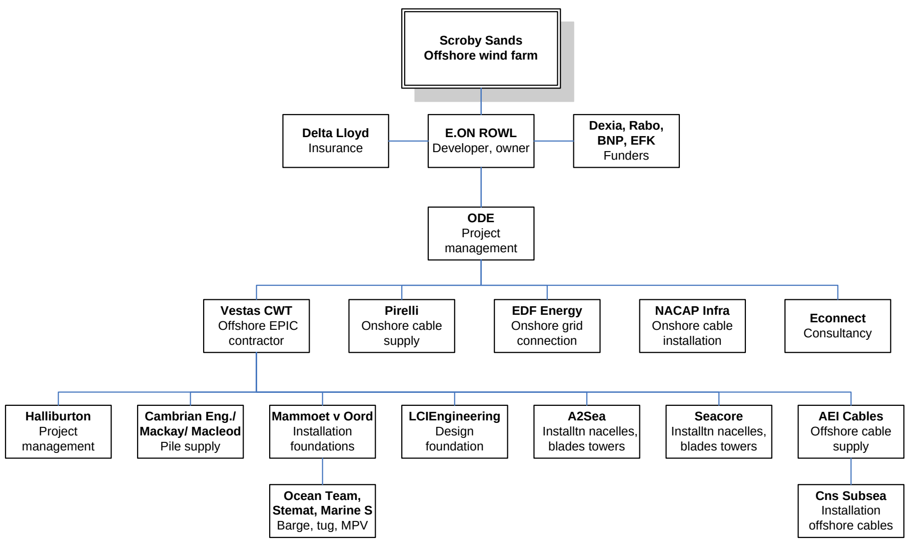


Figure B.6: Scroby Sands project schedule, United Kingdom. *Source:* ([89], [76])

Appendix C

Activities and parts of the six cases

C.1 Explanation

The tables underneath are Supply Chain-Based Tables (SCBT) for the six cases in Denmark, the Netherlands and the United Kingdom. Each box represents an actors for a certain activity and a certain part. The first column shows who is responsible for the contracting for this part: the contractor to the developer or main contractor. The next columns show how actually performs the activity (the name in the box) and by whom this actor was contractor was hired (the colour of the outline of the box). The colour of the outline of the box corresponds to the fill-colour of the box in the first column with the name of the contractor.

In some cases the contractor in the first column is not hired by the main contractor or developer directly, but is subcontracted by the contractor to the developer or main contractor. This is represented in the box by two names in the following manner: 'subcontractor (contractor)'.

C.2 Tables

General supply chain

Horns Rev	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Vestas (Elsam)	Vestas	Vestas	Vestas	Vestas	Port of Esbjerg	A2Sea	A2Sea / Vestas	Vestas
Tower	Vestas (Elsam)	Vestas	Vestas	Vestas	Vestas	Port of Esbjerg	A2Sea	A2Sea / Vestas	
Blade	Vestas (Elsam)	Vestas	Vestas	Vestas	Vestas	Port of Esbjerg	A2Sea	A2Sea / Vestas	
Foundation	MT Højgaard (Elsam)	MT Højgaard	SIF group, Rheden Steel	MT Højgaard		Port of Esbjerg	Mammoet van Oord	Mammoet van Oord	
Infield cable	Nexans (Elsam)	Nexans	Nexans				Global Marine Systems	Global Marine Systems	
Export cable	Nexans (Eltra)	Nexans	Nexans				JD Contractor *(H.P. Lading)*	JD Contractor *(H.P. Lading)*	
Onshore cable	ABB (Eltra)	ABB	ABB					ABB	
Onshore works	ABB (Eltra)	ABB						ABB	ABB
Offshore station	HBG (Eltra)	HBG	HBG	Smit			Smit *(Asian Hercules)*	Smit *(Asian Hercules)*	HBG
Transformer/el system	Alstom (Eltra)	Alstom	Alstom	Alstom					

Parts

Figure C.1: Supply Chain-Based Table for Horns Rev wind farm

General supply chain

Nysted	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Bonus	Bonus	Bonus	Bonus	Bonus	Bonus	A2Sea	A2Sea *(Ocean Ady of Oion PEP shipping)*	Bonus
Tower	Bonus	Bonus	Bonus	Bonus	Bonus	Bonus	A2Sea	A2Sea	
Blade	Bonus	Bonus	Bonus	Bonus	Bonus	Bonus	A2Sea	A2Sea	
Foundation	Aarsleff/ Ballast Nedam	Aarsleff & COWI	Aarsleff A/S				Ballast Nedam *(Eide barge 5 for lift)*	Ballast Nedam	
Infield cable	ABB	ABB	ABB				Mika A/S	Mika A/S	
Export cable	Pirelli	Pirelli	Pirelli				*(Atlantis)*	JD Contractor A/S	
Onshore cable	ABB	ABB	ABB					ABB	
Onshore works	ABB	ABB	ABB					ABB	ABB
Offshore station	Bladt	ISC	Bladt/Semco				DEME	DEME *(Scaldis' Rambiz)*	Bladt
Transformer/el system	Bladt	ISC / SEAS	ABB / Tironi /						Bladt

Parts

Figure C.2: Supply Chain-Based Table for Nysted wind farm

Offshore Windpark Egmond aan Zee (OWEZ)	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Vestas (BCE)	Vestas	Vestas	A2Sea	Vestas	IJmuiden	Vestas	A2Sea	Vestas
Tower	Vestas (BCE)	Vestas	Vestas	A2Sea	Vestas	IJmuiden	Vestas	A2Sea	
Blade	Vestas (BCE)	Vestas	Vestas	Ter Linden	Vestas	IJmuiden	Vestas	A2Sea	
Foundation	Ballast Nedam (BCE)	IC&E (BN)	Bladt	Smit		IJmuiden	Ballast Nedam	Ballast Nedam, IHC, Densit	(Scour: Boskalis)
Infield cable	Ballast Nedam (BCE)	Prysmian IT	Prysmian IT				Ocean Team	Ocean Team (&Global Marine)	
Export cable	Ballast Nedam (BCE)	Prysmian IT	Prysmian IT				Ocean Team	Ocean Team (&Global Marine)	
Onshore cable	Ballast Nedam (BCE)	Prysmian NL	Prysmian NL				Ocean Team	Ocean Team (&Global Marine)	
Onshore works	Strukton (BCE)	Strukton, T&E Consult	Strukton					Strukton	Strukton
Offshore station									
Transformer/el system	Strukton (BCE)	T&E Consult	Ganz				Ganz		Strukton/ Ganz

General supply chain; Parts

Figure C.3: Supply Chain-Based Table for OWEZ wind farm

Q7 / Princess Amalia Park	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Vestas	Vestas	Vestas	Ter Linden/ Blue Water	Vestas	IJmuiden	A2Sea	A2Sea	Vestas
Tower	Vestas	Vestas	Vestas	A2Sea	Vestas	IJmuiden	A2Sea	A2Sea	
Blade	Vestas	Vestas	Vestas	Ter Linden/ Blue Water	Vestas	IJmuiden	A2Sea	A2Sea	
Foundation	Van Oord Van Oord	Smulders, SIF	Smulders, SIF	Smit		IJmuiden	Mammoet van Oord	Mammoet van Oord	
Infield cable	Van Oord	ABB	ABB				Van Oord Offshore	Van Oord Offshore	
Export cable	Van Oord	ABB	ABB				Van Oord Offshore	Van Oord Offshore	
Onshore cable	Van Oord	ABB	ABB					Van Oord	
Onshore works	Van Oord								
Offshore station	Bladt (van Oord)	Bladt	Bladt				Mammoet van Oord	Mammoet van Oord	
Transformer/el system	Bladt (van Oord)	ABB	ABB					Semco	Semco

General supply chain; Parts

Figure C.4: Supply Chain-Based Table for Princess Amalia Wind Park

General supply chain

Burbo Bank	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Siemens	Siemens	Siemens	Siemens	Siemens	Mostyn *1	Mammoet v Oord *2	Mammoet v Oord	Siemens *3
Tower	Siemens	Siemens	Siemens	Siemens	Siemens	Mostyn	Mammoet v Oord *2	Mammoet v Oord	
Blade	Siemens	Siemens	Siemens	Siemens	Siemens	Mostyn	Mammoet v Oord *2	Mammoet v Oord	
Foundation	MT Hojgaard	Ramboll	Smulders/CIF	Mammoet v Oord			Mammoet v Oord	Mammoet v Oord	
Infield cable	ABB	ABB*4	ABB						
Export cable	ABB	ABB	ABB						
Onshore cable									
Onshore works									
Offshore station	EDF Energy	Kedrale							
Transformer/el system									

Parts

*1 (45000 m2)
*2 (Jumping Jack)
*3 +5yr S&M
*4 (36 kV XLPE)
(hammer MENCK 6-2-06)

Sources: www.ramboll-wind.com, www.abb.com, www.dong.com,

Figure C.5: Supply Chain-Based Table for Burbo wind farm

General supply chain

Scroby Sands	Contracting	Design	Manufacturing	Transport	Onshore assembly	Onshore storage	Transport to site	Installation	Commissioning
Nacelle	Vestas CWT	Vestas	Vestas	Vestas	Vestas	Vestas Celtic (at SLP Engineering Lowestoft Yard)	A2Sea / Seacore (shallow)	A2Sea / Seacore (shallow)	Vestas
Tower	Vestas CWT	Vestas	Vestas	Vestas	Vestas	Vestas Celtic (at SLP Engineering Lowestoft Yard)	A2Sea / Seacore (shallow)	A2Sea / Seacore (shallow)	
Blade	Vestas CWT	Vestas	Vestas	Vestas	Vestas	Vestas Celtic (at SLP Engineering Lowestoft Yard)	A2Sea / Seacore (shallow)	A2Sea / Seacore (shallow)	
Foundation	Vestas CWT	LCI Engineering	Cambrian Eng. / Isleburn Mackay& MacLeod	(by manufacturer)		Vestas Celtic (at SLP Engineering Lowestoft Yard)	Mammoet v. Oord	Mammoet v. Oord (Jumping Jack)	
Infield cable	Vestas CWT	AEI Cables	AEI Cables				CNS Subsea	CNS Subsea	
Export cable	Vestas CWT	AEI Cables	AEI Cables				CNS Subsea	CNS Subsea	
Onshore cable	Pirelli NACAP	Pirelli	Pirelli	Pirelli			NACAP	NACAP	
Onshore works	EDF	EDF (onshore station adaptations)						EDF	EDF
Offshore station									
Transformer/el system									

Parts

Figure C.6: Supply Chain-Based Table for Scroby Sands wind farm

Appendix D

Interaction Diagrams

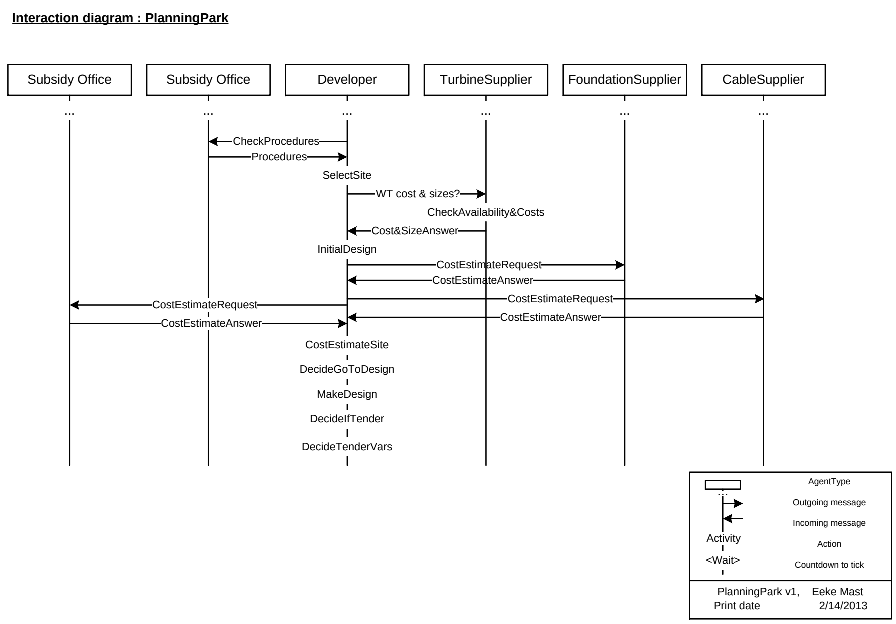


Figure D.1: Interaction diagram for PlanningPark

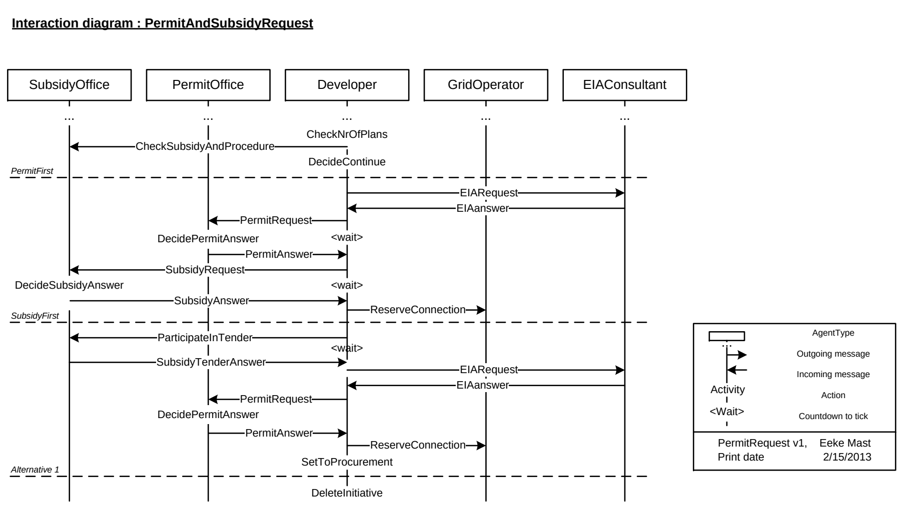


Figure D.2: Interaction diagram for PermitAndSubsidyRequest

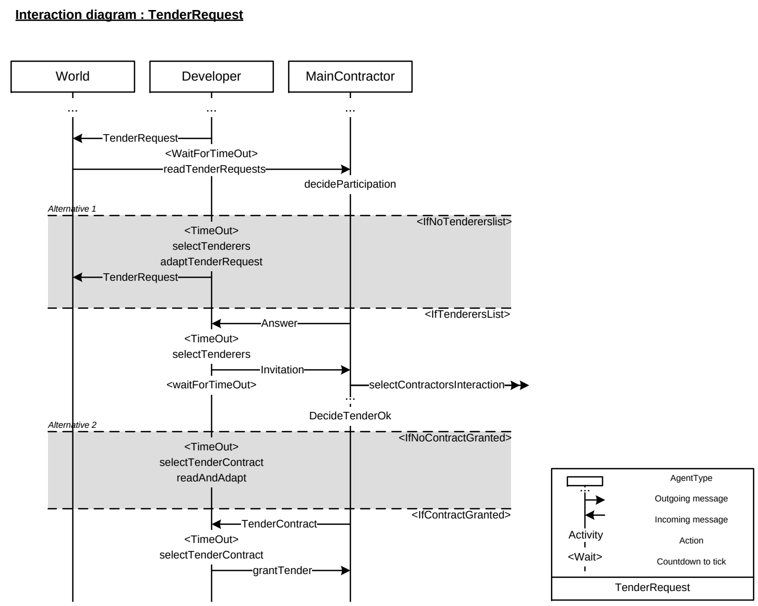


Figure D.3: Interaction diagram for TenderRequest

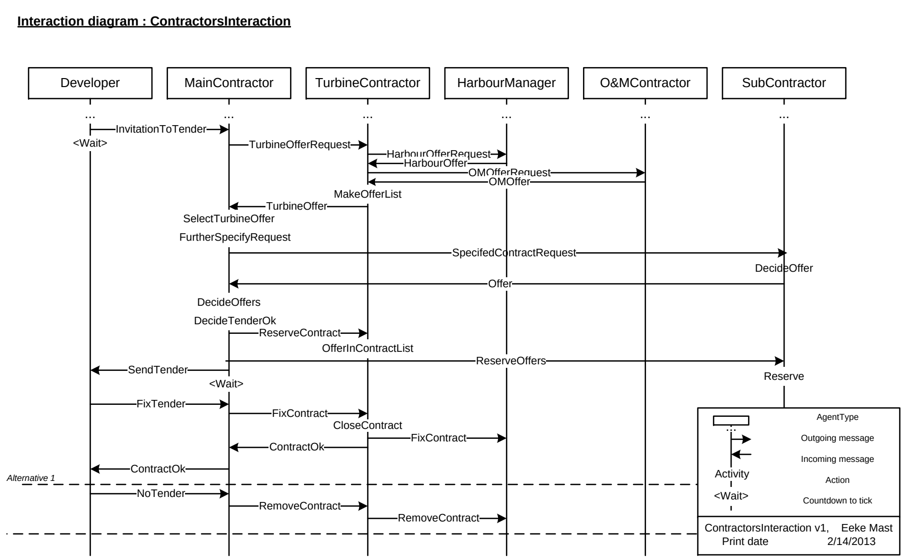


Figure D.4: Interaction diagram for ContractorsInteraction

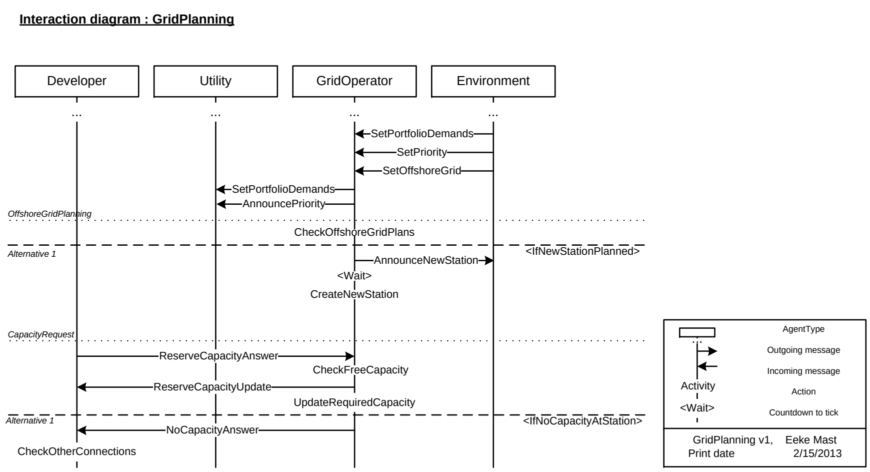


Figure D.5: Interaction diagram for GridPlanning

Appendix E

Sensitivity analysis

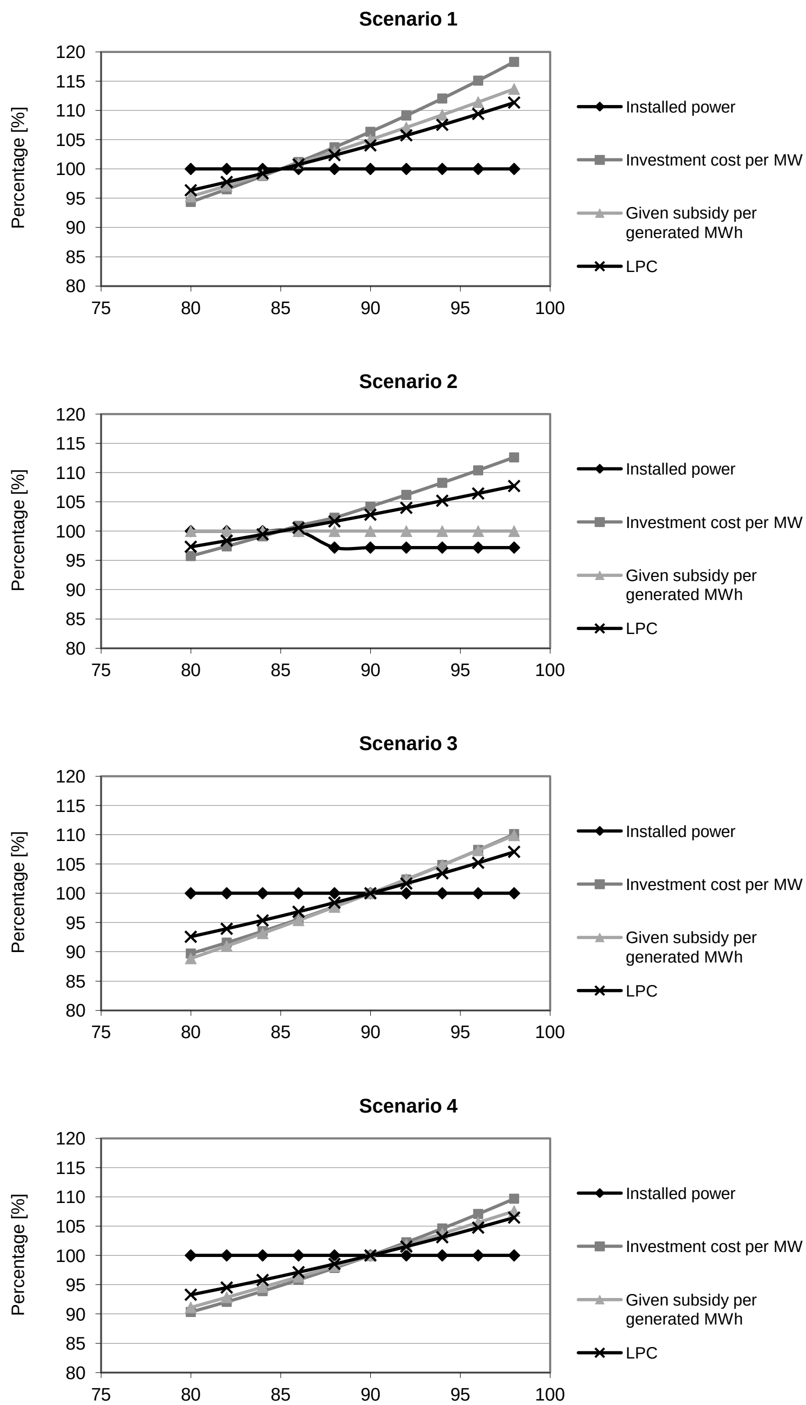


Figure E.1: Wind turbine progress ratio

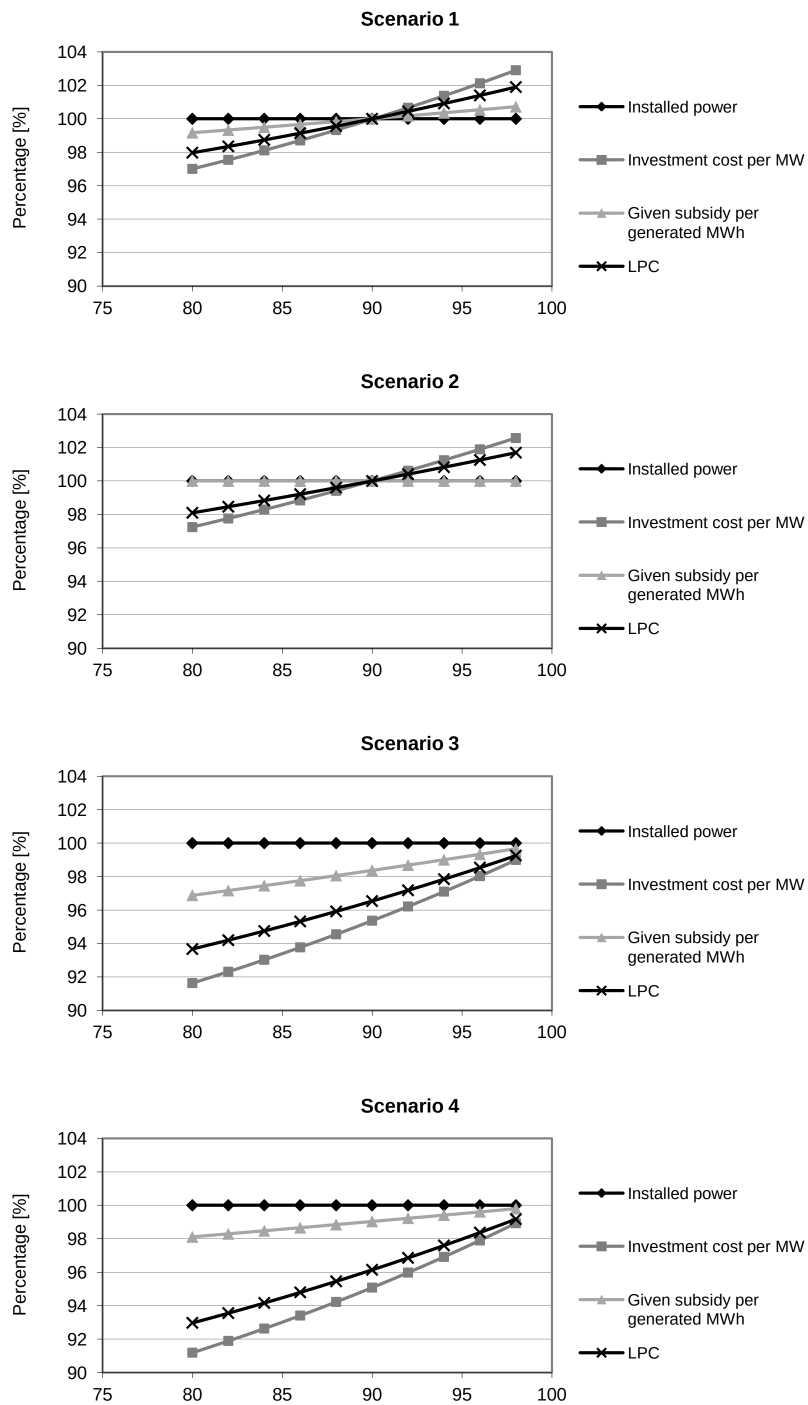


Figure E.2: Grid connection progress ratios

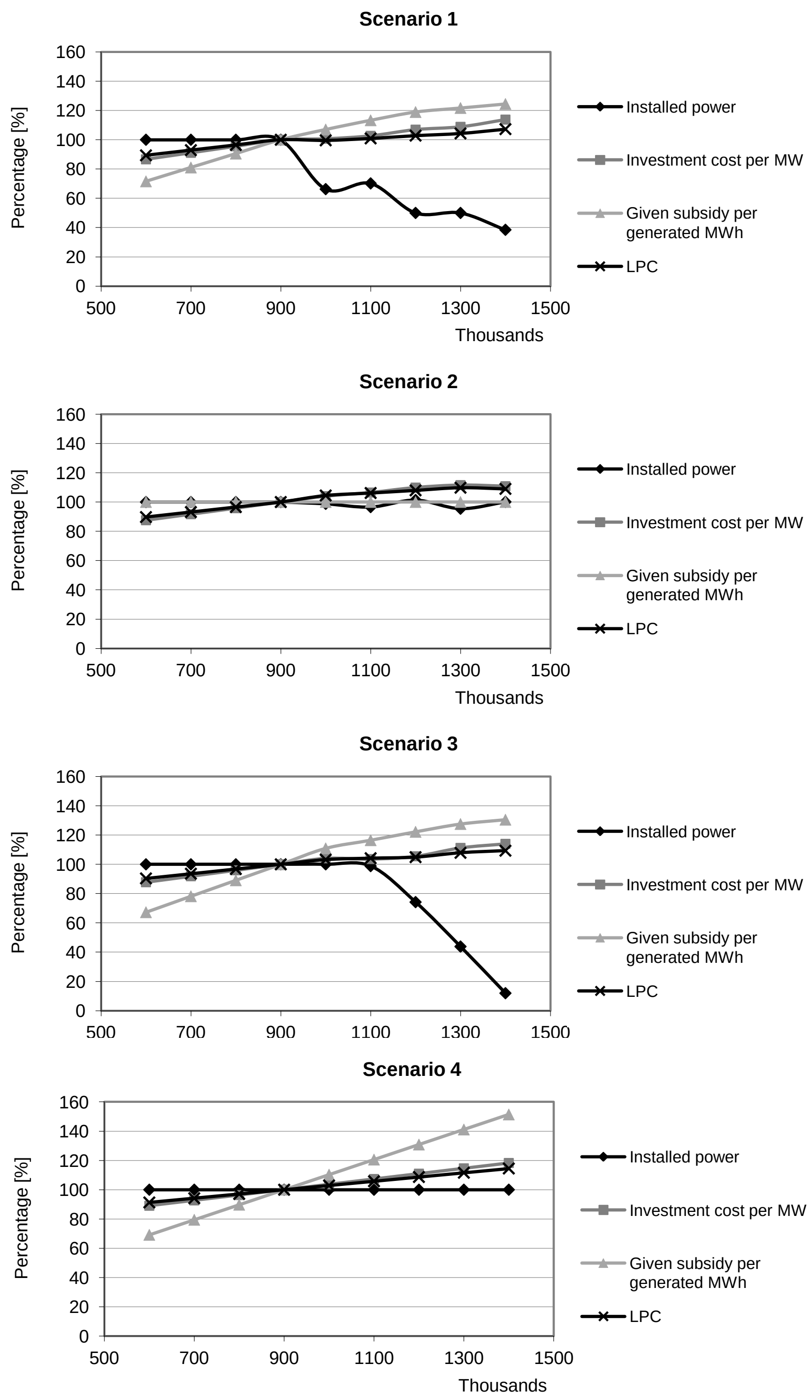


Figure E.3: Wind turbine start cost

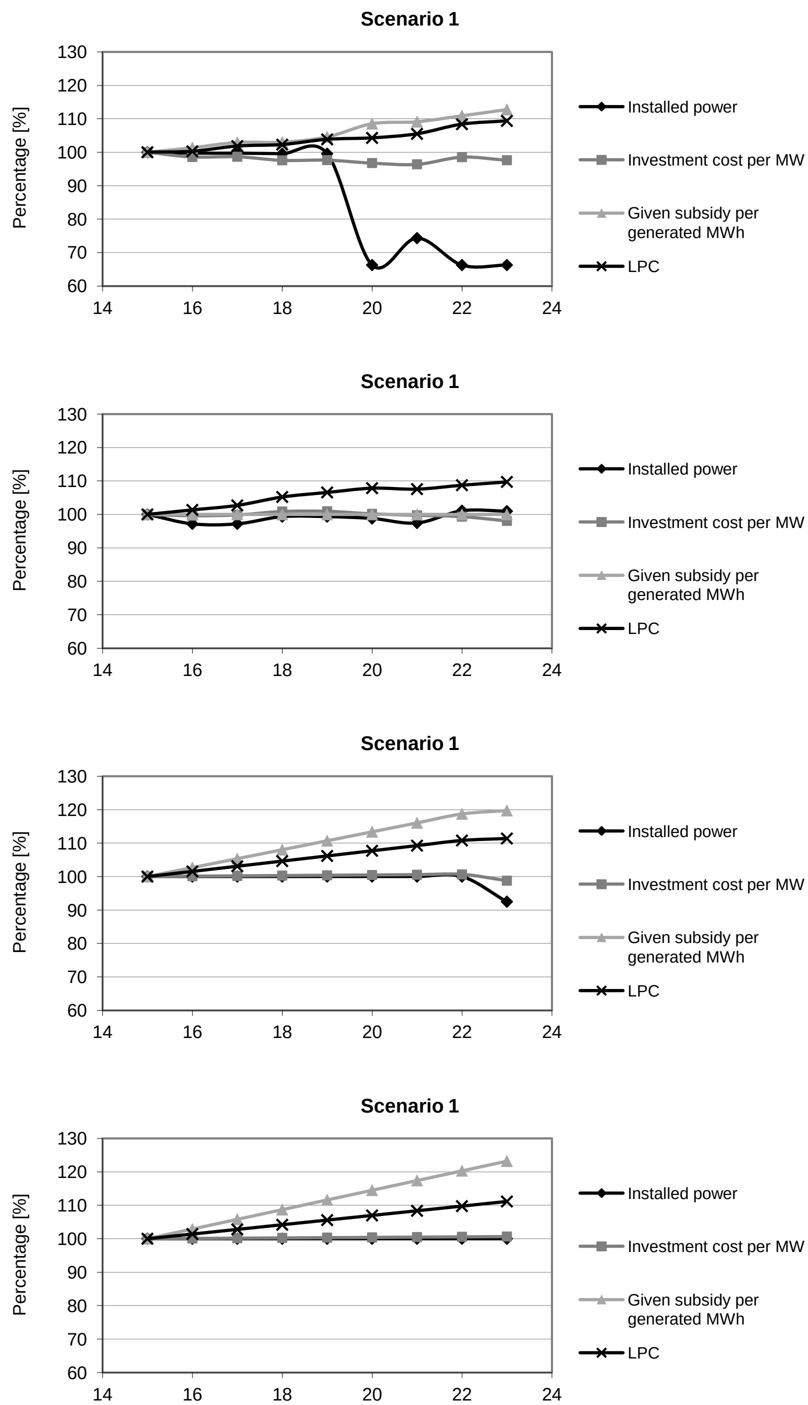


Figure E.4: O&M cost per MWh

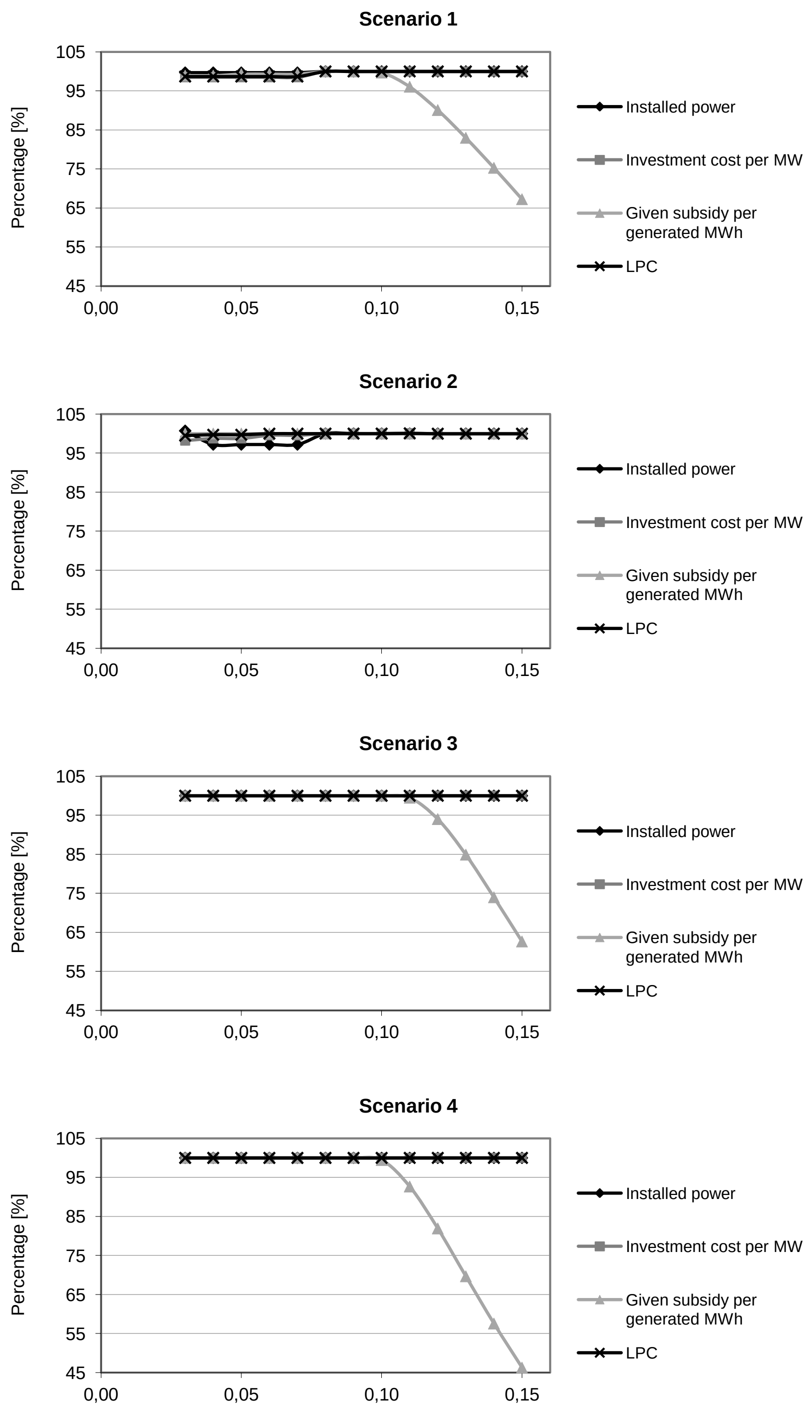


Figure E.5: Electricity price

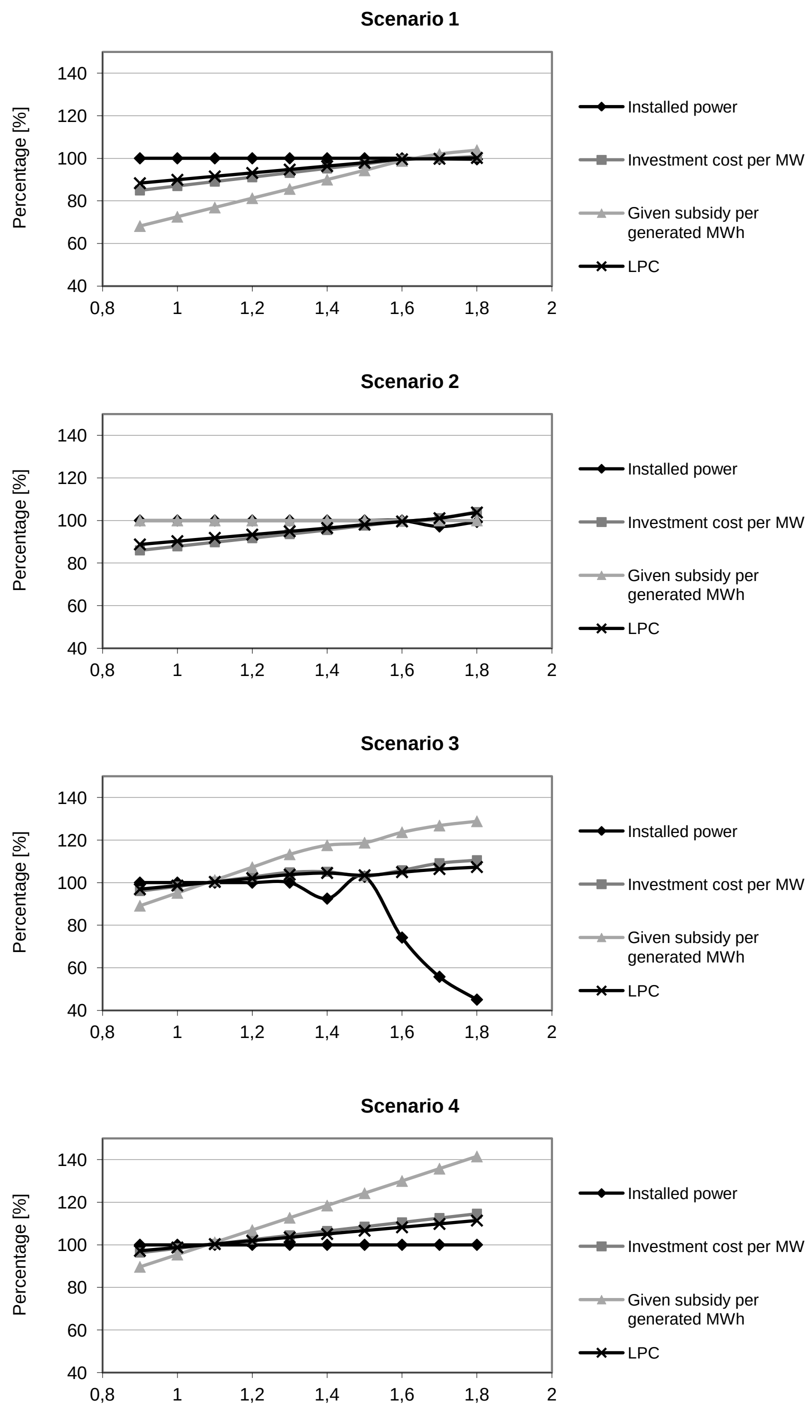


Figure E.6: Steel price

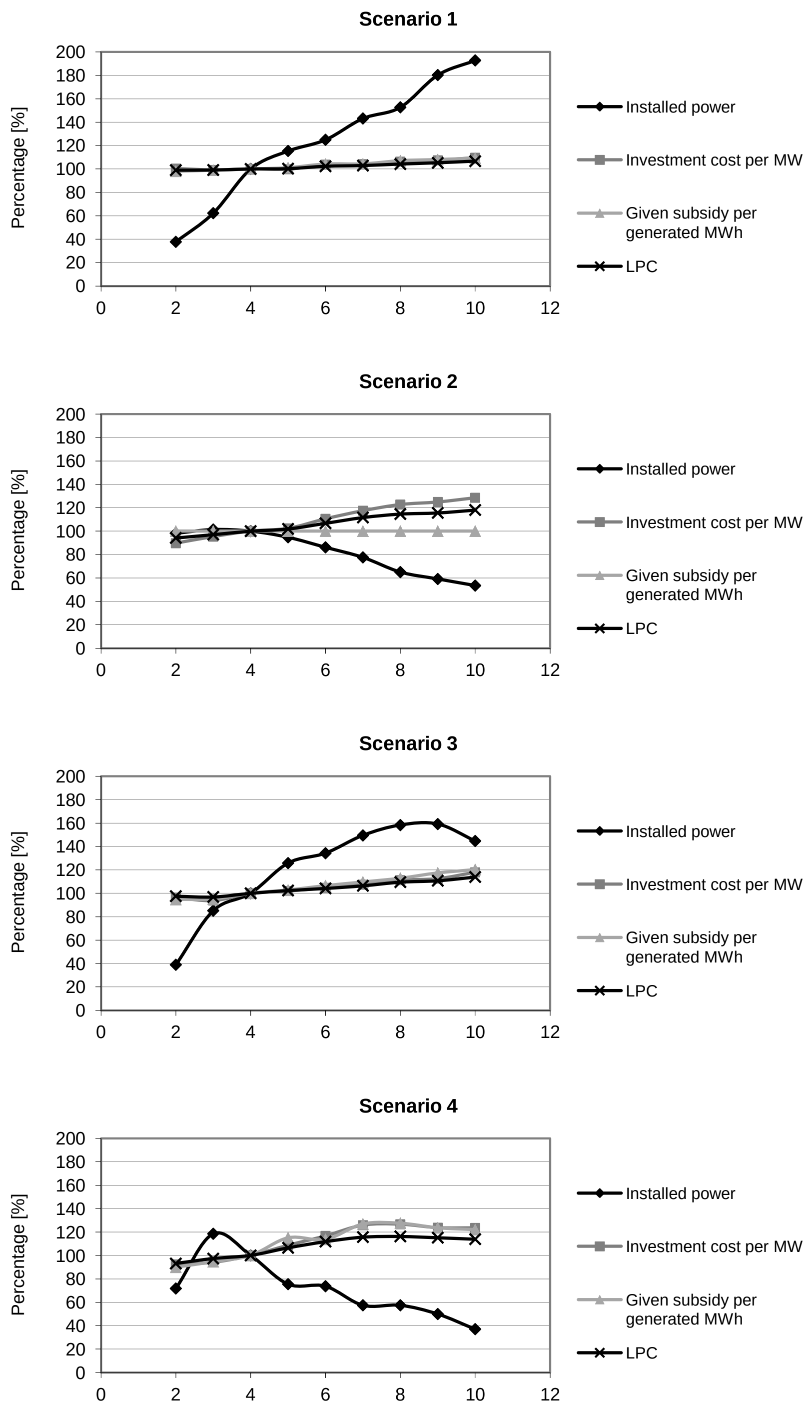


Figure E.7: Number of developers

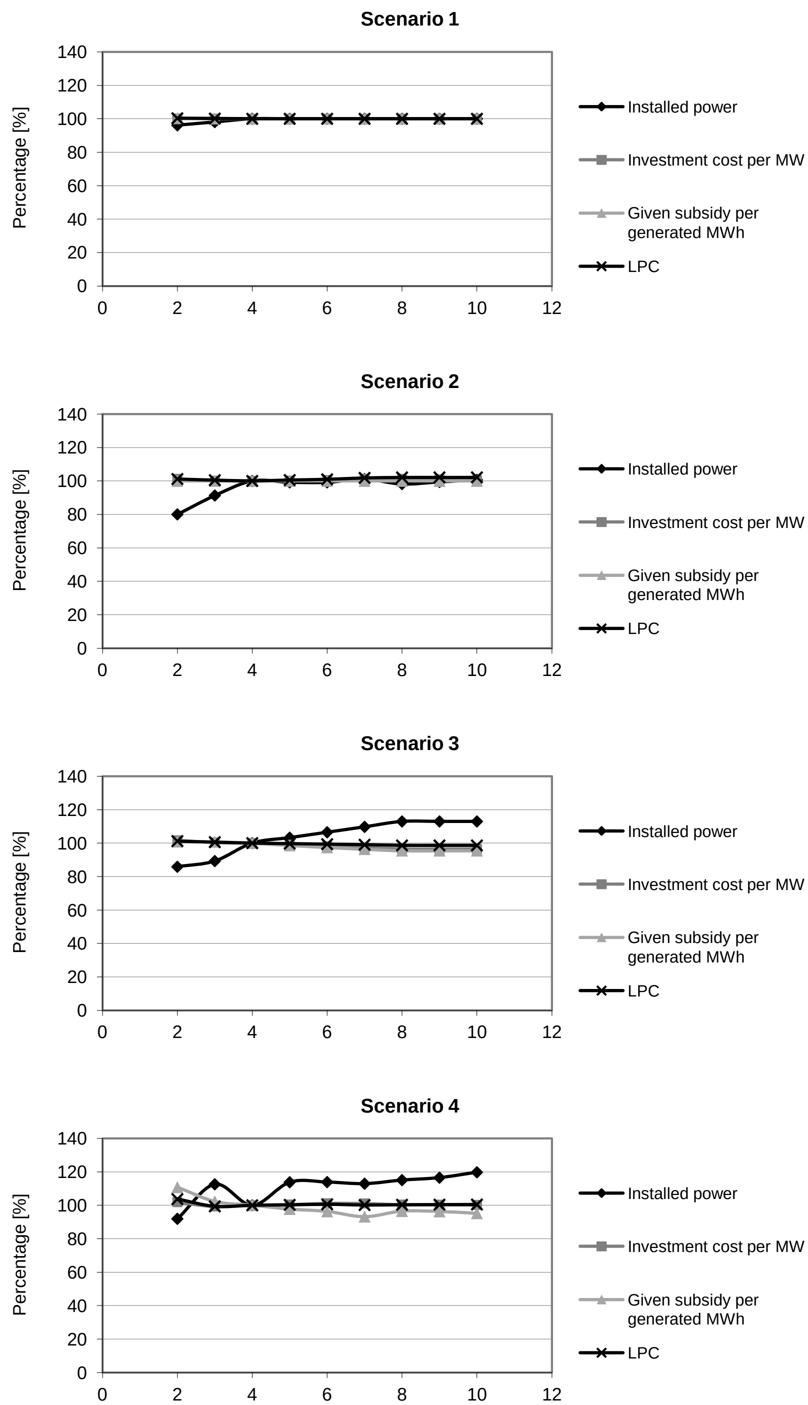


Figure E.8: Number of wind turbine suppliers

Bibliography

[1] Aerogenerator. http://www.windpower.ltd.uk/, Website last visited November 2012.

[2] Danish Energy Agency. http://ens.dk, Website last visited February 2010.

[3] Susanne Agterbosch, Walter Vermeulen, and Pieter Glasbergen. Implementation of wind energy in the Netherlands: the importance of the social-institutional setting. *Energy Policy*, 32(18):2049–2066, 2004.

[4] B. Alboyaci and B. Dursun. Grid Connection Requirements for Wind Turbine Systems in selected countries. Comparison to Turkey. *Electrical Power Quality & Utilization Magazine*, 3(2), 2008.

[5] Ampelmann. http://www.ampelmann.nl/, Website last visted September 2009.

[6] M. Aoki. *Institutions, contracts and organisations*, chapter Institutional evolution as punctuated equilibria, pages 11–33. Edward Elgar, 2000.

[7] Siemens News Archive. http://www.siemens.co.uk/en/news_press/index/news_archive/siemens-to-supply-300-wind-turbines-to-dong-energy.htm, Website last visited November 2012.

[8] Siemens News Archive. http://www.siemens.co.uk/pool/news_press/news_archive/pdfs/siemens-first-6-megawatt-turbine.pdf, Website last visited November 2012.

[9] Vestas News Archive. http://www.vestas.com/en/media/news/news-display.aspx?action=3\&NewsID=3161, Website last visited November 2012.

[10] T. Ashuri. as PhD researcher in the Innwind project, at the TUDelft. Personal communication, 12 April 2010.

[11] T. Ashuri. *Beyond Classical Upscaling: Integrated Aeroservoelastic Design and Optimization of Large Offshore Wind Turbines.* Delft University of Technology, 2012.

[12] European Wind Energy Association. http:\\www.ewea.org, Website last visited July 2010.

[13] S. Awerbuch. Wind economics in the 21st century. *Wind Directions*, pages 44–47, January/February 2006.

[14] R. Axelrod. *The evolution of cooperation.* Basic Books, revised edition edition, 1984.

[15] R. Axelrod. Advancing the art of simulation in the social sciences. *Complexity*, 3(2):16–22, 1997.

[16] R. Axelrod. Advancing the art of simulation in the social sciences. *Japanese Journal for Management Information System, Special Issue on Agent-Based Modeling*, 12(3), 2003.

[17] R. Axelrod and D.S. Bennett. A landscape theory of aggregation. *British journal of political science*, 23(2):211–233, 1993.

[18] R. Axtell. Why agents? On the varied motivations for agent computing in the social sciences. In *Proceedings of the workshop on agent simulation: applications, models and tools*, 1999.

[19] A.J. Bagnall and G.D. Smith. A multi-agent model of the UK market in electricity generation. *Applications of Learning Classifier Systems*, 2004.

[20] BARD. `http://www.bard-offshore.de/en`, Website last visited June 2010.

[21] J.M. Bauer and P.M. Herder. *Philosophy of technology and engineering sciences*, volume 8 of *Handbook of the Philosopht of science*, chapter Designing socio-technical systems, pages 597–625. Elsevier, 2009.

[22] Beatrice. `http://www.beatricewind.co.uk/`, Website last visited september 2009.

[23] W.E. Bijker. *Of bicycles, bakelites, and bulbs: Toward a theory of sociotechnical change.* The MIT Press, 1997.

[24] E. Bonabeau. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(Suppl 3):7280, 2002.

[25] G. Booch, J. Rumbaugh, and I. Jacobson. *The Unified Modeling Language User Guide.* The Addison-Wesley Object Technology Series. Addison-Wesley Professional, 2005.

[26] Jan Boorsma. Project Director Westereems. Interview, 23 October 2008.

[27] P. Bresciani, A. Perini, P. Giorgini, F. Giunchiglia, and J. Mylopoulos. Tropos: An agent-oriented software development methodology. *Autonomous Agents and Multi-Agent Systems*, 8(3):203–236, 2004.

[28] D.G. Brown. *The Earths Changing Land: An Encyclopedia of Land-Use and Land-Cover Change*, chapter Agent-based models, pages 7–13. Westport CT: Greenwood Publishing Group, 2006.

[29] J.M. Bryson. What to do when stakeholders matter, Stakeholder Identification and Analysis Techniques. *Public Management Review*, 6(1):21–53, 2004.

[30] BTM Consult. International Wind Energy Development. *World Market Update 2007*, March 2008.

[31] B.H. Bulder and et al. The Icorass feasibility study - final report. Technical Report ECN-E–07-010, Energy research Centre of the Netherlands (ECN) & Delft University of Technology, 2007.

[32] DW Bunn and FS Oliveira. Agent-based simulation-an application to the new electricitytrading arrangements of England and Wales. *IEEE transactions on Evolutionary Computation*, 5(5):493–503, 2001.

[33] D.W. Bunn and F.S. Oliveira. Evaluating individual market power in electricity markets via agent-based simulation. *Annals of Operations Research*, 121(1):57–77, 2003.

[34] G.J.W. van Bussel and M.B. Zaaijer. DOWEC concepts study, reliability, availability and maintenance aspects. In *Proceedings of the European Wind Energy Conference and Exhibition 2001*, Copenhagen, Denmark, July 2001.

[35] Sabine Christiansen. Towards good environmental status, a network of marine protected areas for the north sea, summary version. Technical report, WWF Germany, Frankfurt am Main, April 2009.

[36] K.B. Clark. The interaction of design hierarchies and market concepts in technological evolution. *Research Policy*, 14(5):235–251, 1985.

[37] M. Clarke and E. Holm. Microsimulation methods in spatial analysis and planning. *Geografiska Annaler, Series B, Human Geography*, 69(2):145–164, 1987.

[38] R.H. Coase. The nature of the firm. *Economica*, 4(16):386–405, 1937.

[39] J.F. Coates. Scenario planning. *Technological forecasting and social change*, 65(1), 2000.

[40] A. Cockburn. *Writing Effective Use Cases.* Addison-Wesley Professional, 2000.

[41] N. Collier. Repast: An Extensible Framework for Agent Simulation. Working paper, Social Science Research Computing, University of Chicago, 2001.

[42] European Commission. Externalities of Fuel Cycles. DG XII Science, Research and Development, JOULE. ExternE Externalities of Energy. Volume 6: Wind and Hydro. Technical Report EUR 16521, 1995.

[43] European Commission. Energy for the future: Renewable sources of energy. White Paper for a Community Strategy and Action Plan COM(97)599 final, November 1997.

[44] European Commission. External costs, research results on socio-environmental damages due to electricity and transport. Community research EU 20198, 2003.

[45] European Commission. Directive 2009/28/EC of the European Parliament and of the Council. Official journal of the European Union, 23 April 2009.

[46] B. Coriat and G. Dosi. *Evolutionary and Regulationist Research Programmes*, chapter The institutional embeddedness of economic change: an appraisal of the 'evolutionary' and regulationist' research programmes. Edward Elgar, Cheltenham, 1998.

[47] Global Wind Energy Council and Greenpeace. Global wind energy outlook 2008, 2008.

[48] K. Cuhls. Delphi method. Available at `http://www.unido.org/fileadmin/import/16959_DelphiMethod.pdf`, Fraunhofer Institute for Systems and Innovation Research. Germany, 2003.

[49] Financiëel dagblad. `http://beurs.fd.nl`, Website last visit February 2013.

[50] J. Dam. Offshore wind farm eia issues - practical experiences in some countries. Annex 23: Workshop Offshore wind energy: Ecology and Regulation, February 2008.

[51] Koen Haziël Dam, Igor Nikolic, and Zofia Lukszo, editors. *Agent-based modelling of socio-technical systems.* Springer, 2013.

[52] E. Dammers. *Leren van de toekomst, Over de Rol Van Scenarios Bij Strategische Beleidsvorming*. Eburon, Delft, The Netherlands, 2000.

[53] B. Daniëls and S. Kruitwagen. Referentieraming energie en emissies 2010-2020. (ECN-E–10-004), April 2010.

[54] Iigo Martinez de Alegra, Jon Andreu, Jos Luis Martn, Pedro Ibaez, Jos Luis Villate, and Haritza Camblong. Connection requirements for wind farms: A survey on technical requirements and regulation. *Renewable and Sustainable Energy Reviews*, 11(8):1858 – 1872, 2007.

[55] Johan Dekkers. Rapportage Proces vergunningverlening Offshore Windpark Egmond aan Zee. Technical Report OWEZ_R_192_20070820, NoordzeeWind, August 2007.

[56] J.A. Dewar. *Assumption-based planning: a tool for reducing avoidable surprises*. Cambridge University Press, 2002.

[57] Imar Doornbos. Ministry of Economic Affairs, Den Haag. Interview, 4 april 2007.

[58] Giovanni Dosi. Technological paradigms and technological trajectories. *Research Policy*, 11:147–162, 1982.

[59] H. Dotinga and A. Trouwborst. The Netherlands and the Designation of Marine Protected Areas in the North Sea: Implementing International and European Law. *Utrecht Law Review*, 5(1):21–43, 2009.

[60] ODE Limited Douglas Westwood. Scroby sands - supply chain analysis. Technical Report DWL report nr 334-04, DTI, July 2005.

[61] A.W.N. Dril and H. Elzenga. Referentieramingen energie en emissies 2005-2020. Technical Report ECN-C–05-018, Energy research Centre of the Netherlands (ECN), Petten, January 2005. `http://www.ecn.nl/library/reports/2005/c05018.html`.

[62] A. Drogoul, D. Vanbergue, and T. Meurisse. Multi-agent based simulation: where are the agents? *Lecture Notes in Computer Science*, pages 1–15, 2003.

[63] D.E. Duplisea, S. Jennings, K.J. Warr, and T. Dinmore. A size-based model of the impacts of bottom trawling on benthic community structure. *Canadian Journal of Fisheries and Aquatic Science*, 59(11):1785–1795, 2002.

[64] ECN. Offshore wind atlas `http://www.ecn.nl/nl/units/wind/rd-programma/aerodynamica/innovative-applications/offshore-wind-atlas/`, Website last visited July 2010.

[65] Electricity Market Complex Adaptive System EMCAS. `http://www.dis.anl.gov/projects/emcas.html`, Website last visited February 2010.

[66] Enercon. E-126 turns into 7.5 mw turbine. *Windblatt, Enercon magazine for wind energy*, January 2010.

[67] Dong Energy, E.on, and SEAS NVE. Nysted Havwindmœllepark The construction of Nysted Offshore Wind Farm. Leaflet. `http://www.dongenergy.com`.

[68] Dong Energy, Vattenfall, Danish Energy Authority, and Danish Forest & Nature Agency. Danish offshore wind: Key environmental issues. `http:\\www.ens.dk`, November 2006.

[69] B. Enserink. Analyse van complexe omgevingen. Dictaat, TUDelft, 2005.

[70] European Commission. Towards a European strategy for the security of energy supply. Green paper ISBN 92-894-0319-5, Luxembourg Office for Official Publications of the European Communities, 2001.

[71] European Commission. Climate change: Commission welcomes final adoption of Europe's climate and energy package. Press release at `http://europa.eu/`, 17 December 2008.

[72] EWEA. *Wind energy - The Facts: A guide to the technology, economics and future of wind power*. Earthscan, 2009.

[73] EWEA and Greenpeace. Wind force 12. Technical report, May 2003.

[74] G. Fagiolo, C. Birchenhall, and P. Windrum. Empirical validation in agent-based models: Introduction to the special issue. *Computational Economics*, 30(3):189–194, 2007.

[75] Burbo Bank Wind Farm. `http://www.dongenergy.com/Burbo`, Website last visited January 2010.

[76] Scroby Sands Wind Farm. `http://www.eon-uk.com/generation/scrobysands.aspx`, Website last visited April 2013.

[77] M.C. Ferguson, M. Kühn, G.J.W. van Bussel, W. Bierbooms, T.T. Cockerill, B. Göransson, L.A. Harland, J.H. Vugts, and R. Hes. Opti-owecs final report vol. 4: A typical design solution for an offshore wind energy conversion system. *Institute for Wind Energy, Delft*, 1998.

[78] Fichaux, N. et al . Oceans of opportunities, Harnessing Europe's largest domestic energy resource. Offshore report, EWEA, September 2009.

[79] FINO1. `http://fino.bsh.de`, Website last visited August 2009.

[80] T. Fischer, W. Vries, P. Rainey, B. Schmidt, K. Argyriadis, and M. Kühn. Offshore support structure optimization by means of integrated design and controls. *Wind Energy*, 15(1):99–117, 2012.

[81] Concerted Action for Offshore Wind Energy Deployment (COD). Principal findings 2003-2005. Final report, Energie, 2005.

[82] Concerted Action for Offshore Wind Energy Deployment (COD). Work package 3: Legal and administrative issues. Technical report, Energie, 2005.

[83] B. Frank. *Offshore wind energy: research on environmental impacts*, chapter Research on Marine Mammals, Summary and Discussion of Research Results, pages 77–86. Springer Verlag, 2006.

[84] G. Ringland, quoting M. Porter (1985). *Scenario Planning: Managing for the Future*. John Wiley and Sons, Ltd., 1998.

[85] José Manuel Galán, Luis R. Izquierdo, Segismundo S. Izquierdo, José Ignacio Santos, Ricardo del Olmo, Adolfo López-Paredes, and Bruce Edmonds. Errors and artefacts in agent-based modelling. *Journal of Artificial Societies and Social Simulation*, 12(1):1, 2009.

[86] L. Gasser, C. Braganza, and N. Herman. MACE: A flexible testbed for distributed AI research. *Distributed artificial intelligence*, 1:119–152, 1987.

[87] Frank W. Geels and Ren Kemp. Dynamics in socio-technical systems: Typology of change processes and contrasting case studies. *Technology in Society*, 29(4):441 – 455, 2007.

[88] F.W. Geels and J. Schot. Typology of sociotechnical transition pathways. *Research Policy*, 36(3):399–417, 2007.

[89] G. Gerdes, A. Tiedemann, and S. Zeelenberg. Case Study: European Offshore Wind Farms-A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms. Technical report, Deutsche Windguard, Deutsche Energie-Agentur, University of Groningen, 2006.

[90] Intomart GfK. De beleving van het windpark voor de kust van Egmond T3-meting. Technical report, NoordzeeWind Amsterdam, 2009.

[91] Amineh Ghorbani, Pieter Bots, Virginia Dignum, and Gerard Dijkema. MAIA: a framework for developing agent-based social simulations. *Journal of Artificial Societies and Social Simulation*, 16(2):9, 2013.

[92] N. Gilbert. *Multi-Agent Models and Simulation for Social and Human Sciences*, chapter Computational Social Science: Agent-based social simulation. The Bardwell-Press Oxford, 2007.

[93] N. Gilbert and P. Terna. How to build and use agent-based models in the social science. *Mind and society*, 1(1):57–72, 2000.

[94] M. Godet. The art of scenarios and strategic planning: tools and pitfalls. *Technological forecasting and social change*, 65(1):3–22, 2000.

[95] Anna Grandori. A prescriptive contingency view of organizational decision making. *Administrative Science Quarterly*, 29(2):192–209, 1984.

[96] Philip Greenacre, Robert Gross, and Phil Heptonstall. Great Expectations: The cost of offshore wind in UK waters understanding the past and projecting the future. Technical report, UK Energy Research Centre, 2010.

[97] Greenpeace. Offshore wind, onshore jobs; A new industry for Britain, 19 October 2004.

[98] R. Grimble and K. Wellard. Stakeholder methodologies in natural resource management: a review of principles, contexts, experiences and opportunities. *Agricultural Systems*, 55(2):173 – 193, 1997.

[99] J. Groenewegen. *Teaching pluralism in economics*, chapter On pluralism and interdisciplinarity in economics, pages 1–21. Edward Elgar, 2007.

[100] J.P.M. Groenewegen and R.W. Künneke. Process and outcomes of the infrastructure reform: an evolutionary perspective. *Institutional Reform Regulation and Privatization: Process and Outcomes in Infrastructure Industries*, pages 1–36, 2005.

[101] P. Harrenstein and M. de Weerdt. Introduction to Game Theory and Mechanism Design. Lecture for the European Agent System Summer School (EASSS), Ludwig-Maximilians-Universitat, Munich and Delft University of Technology, Delft, Lisbon, 6th May 2008.

[102] K. van der Heijden. Scenarios, strategy and the strategy process. Article, Global Business Network, 2003.

[103] K. van der Heijden. *Scenarios: the art of strategic conversation*. John Wiley & Sons Chichester, UK, 2005.

[104] P.M. Herder, I. Bouwmans, G.P.J. Dijkema, R.M. Stikkelman, and M.P.C. Weijnen. Designing infrastructures using a complex systems perspective. *Journal of Design Research*, 7(1):17–34, 2008.

[105] S.A. Herman and J.T.G. Pierik. Locaties en opwekkosten 6000 MW Offshore Windenergie (Revisie maart 2004). Technical report, Energy Research Centre of the Netherlands (ECN).

[106] L.M. Hermans and W.A.H. Thissen. Actor analysis methods and their use for public policy analysts. *European Journal of Operational Research*, 196(2):808 – 818, 2009.

[107] M. van der Hoeven. Voorzienings- en leveringszekerheid energie; Brief minister over de mogelijkheden van grootschalige opslagsystemen in het Nederlandse elektriciteitssysteem. ET/ED / 8011708, 26 Feb 2008.

[108] Wind Service Holland. `http://home.planet.nl/~windsh/wsh.html`, Website last visited April 2010.

[109] T.P. Hughes. *The social construction of technological systems: new directions in the sociology and history of technology*, chapter The evolution of Large Technological Systems, pages 51–81. MIT Press, 1987.

[110] International Energy Agency (IEA). World energy outlook 2006. Technical report, 2007.

[111] IEEE. Standard for Software Verification and Validation. IEEE Std 1012-2004(Revision of IEEE Std 1012-1998), IEEE Computer Society, New York, USA, 2004.

[112] Concerted Action Offshore Wind Energy in Europe. Offshore wind energy, ready to power a sustainable europe. Final report, December 2001.

[113] Inspraakpunt, government office for consultation in permit procedures. `http:\\www.inspraakpunt.nl`, Website last visited January 2010. Old url, new url is `http:\\www.centrumpp.nl`.

[114] M.A. Janssen and E. Ostrom. Empirically based, agent-based models. *Ecology and Society*, 11(2):37, 2006.

[115] C. Januário, S. Semino, and M. Bell. Offshore Windfarm Decommissioning: A proposal for guidelines to be included in the European Maritime Policy. May 2007.

[116] N.R. Jennings. On agent-based software engineering. *Artificial Intelligence*, 117:277–296, 2000.

[117] U.K. Jørgensen. Turnkey contract vs. multi contracts. Copenhagen Offshore Wind Power Conference, 26-28 October 2005. Elsam Engineering.

[118] M. Junginger. Learning in renewable energy technology development. Technical report, Copernicus Institute, Utrecht University, 2005.

[119] M. Junginger, S. Agterbosch, A. Faaij, and W. Turkenburg. Renewable electricity in the netherlands. *Energy Policy*, 32(9):1053–1073, 2004.

[120] M. Junginger, A. Faaij, and W.C. Turkenburg. Cost reduction prospects for offshore wind farms. *Wind Engineering*, 28(1):97–118, 2004.

[121] L. Kamp. *Learning in wind turbine development a comparison between the Netherlands and Denmark*. PhD thesis, 2002.

[122] M. Klaes and E.M. Sent. A conceptual history of the emergence of bounded rationality. *History of political economy*, 37(1):27–59, 2005.

[123] W.L. Kling, B.C. Ummels, and R.L. Hendriks. Transmission and System Integration of Wind Power in the Netherlands. In *IEEE Power Engineering Society General Meeting, 2007*, pages 1–6, 2007.

[124] J. Koppenjan and J. Groenewegen. Institutional design for complex technological systems. *International Journal of Technology, Policy and Management*, 5(3):240–257, 2005.

[125] R.W. Künneke. Institutional reform and technological practice: the case of electricity. *Industrial and Corporate Change*, 17(2):233–265, 2008.

[126] P. Lako and L.W.M. Beurskens. Windenergie op zee als onderdeel van de duurzame energiedoelstelling. Informatie ten behoeve van een PlanMER Noordzee van het Ministerie van Verkeer en Waterstaat ECN-E–10-052, Energy research Centre of the Netherlands (ECN), June 2010.

[127] Reinier Hille Ris Lambers. Imares. interview, September 2009.

[128] L. Lemay and R. Cadenhead. *SAMS' Teach yourself Java 2 in 21 days.* SAMS, 4 edition, 2004.

[129] J.K. Lemming, P.E. Morthorst, and N.E. Clausen. Offshore wind power experiences, Potential and key issues for deployment. Technical Report Risø-R-1673(EN), Risø Natonal Laboratory for Sustainable Energy Roskilde, January 2008.

[130] M. Leopold. Offshore wind farms; sea mammals and seabirds. Annex 23: Workshop Offshore wind energy: Ecology and Regulation, February 2008.

[131] A. Lindeboom. Research in offshore wind parks. Annex 23: Workshop Offshore wind energy: Ecology and Regulation, February 2008.

[132] H. Lindeboom, J. Geurts van Kessel, and L. Berkenbosch. Gebieden met bijzondere ecologische waarden op het nederlands continentaal plat. Rapport RIKZ/2005.008 Alterra Rapport nr. 1109, RIKZ and Alterra, April 2005. ISBN nr. 90-369-3415-X.

[133] H.J. Lindeboom, H.J. Kouwenhoven, M.J.N. Bergman, S. Bouma, S. Brasseur, R. Daan, R.C. Fijn, D. de Haan, S. Dirksen, R. van Hal, et al. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, 6(3):035101, 2011.

[134] C.M. Macal and M.J. North. Tutorial on agent-based modeling and simulation. In *Proceedings of the 37th conference on Winter simulation*, page 15. Winter Simulation Conference, 2005.

[135] C.M. Macal and M.J. North. Tutorial on agent-based modeling and simulation part 2: how to model with agents. In *Proceedings of the 37th conference on Winter simulation*. Winter Simulation Conference, 2006.

[136] M.W. Macy and R. Willer. From factors to actors: Computational Sociology and Agent-Based Modeling. *Annual review of sociology*, 28(1):143–166, 2002.

[137] Marico Marine. Investigation of Technical and Operational Effects on Marine Radar Close to Kentish Flats Offshore Wind Farm. Research document for bwea, dti, mca, port of london, April 2007.

[138] E.H.M. Mast. Verslag Group Decision Room bijeenkomst 1 juli 2005. Technical Report WE-05197, Wind Energy Research Group, DUWIND, Delft, July 2005.

[139] H.G. Matthies, C. Nath, T.E. Schellin, A.D. Garrad, M.A. Wastling, M.A. Quarton, J. Wei, M. Scherweit, and T. Siebers. Study of offshore wind energy in the ec. JOULE I JOUR 0072, Verlag Naturliche Energie, Brekendorf, 1995.

[140] P. McBurney. Comment on website. http://www.cscs.umich.edu/ crshalizi/notabene/agent-based-modeling.html, Last visited Sept 2009.

[141] Ian Miles. Scenario planning. Foresight Methodologies - Training Module 2 V.03-87775, UNIDO, Vienna, 2003.

[142] Ministries of VROM, LNV, V& W and EZ. Nota Ruimte, Ruimte voor Ontwikkeling. PKB Nationaal Ruimtelijk Beleid, 2004.

[143] Ministries of VROM, LNV, VenW and EZ. Integraal Beheerplan Noordzee 2015 (North Sea Management Plan 2015), July 2005.

[144] Ministry of Economic Affairs. Brief minister aan Tweede Kamer, 20 augustus 2009, ET/ED / 9145414.

[145] Ministry of Economic Affairs. Regeling van de minister van Economische Zaken van 18 november 2009 nr. WJZ/9203919 (Regeling windenergie op zee 2009). Staatscourant nr 2009 nr. 17851, 24 November 2009.

[146] Ministry of Economic Affairs, Agriculture and Innovation. Kamerbrief over de openstelling van de regeling SDE+ d.d. 22 april 2011 .

[147] Ministry of Economic Affairs, Agriculture and Innovation. Kamerbrief Reactie op uw brief aangaande schaliegas.

[148] Ministry of Economic Affairs, Agriculture and Innovation. Convenant tussen Q10 Offshore Wind B.V. en de Staat der Nederlanden ter zake van de realisatie van innovatieve ontwikkelingen en extra capaciteit bij de bouw van een windturbinepark op de locatie Q10. Staatscourant nr 21120, 24 November 2011.

[149] Ministry of Housing, Spatial Planning and the Environment et al. Nieuwe energie voor het klimaat, Werkprogramma Schoon en Zuinig, September 2007.

[150] Ministry of Transport, Public Works and Water Management. Beleidsregels inzake toepassing Wet beheer rijkswaterstaatswerken op installaties in de exclusieve economische zone. Staatscourant nr 252, 29 Dec 2004.

[151] Ministry of Transport, Public Works and Water Management. Ontwerp-besluit inzake aanvraag Wbr-vergunning offshore windturbinepark 'Katwijk', 17 Sep 2007.

[152] Ministry of Transport, Public Works and Water Management. Ontwerp Nationaal Waterplan, December 2008.

[153] Ministry of Transport, Public Works and Water Management. Besluit inzake aanvraag Wbr-vergunning offshore windturbinepark 'Beaufort'. WSV/2009-912, 29 Dec 2009.

[154] R. de Mooij and P. Tang. Four futures for europe. Technical report, CPB, 2003.

[155] P.E. Morthorst, S.G. Jensen, C. Huber, G. Resch, and M. Ragwitz. OPTRES: Assessment and optimisation of renewable support schemes in the European electricity market, WP 6 Interactions with other policies and markets. Final Report EIE/04/073/S07.38567, Altener, 2006.

[156] J. Murphy. `http://www.u.arizona.edu/~jtmurphy/H2R/main.htm`, Website last visited August 2009.

[157] C. Mutze. The employment potential of a dutch offshore wind energy market. Technical report, Utrecht University, performed at Delft University of Technology, 2007.

[158] L. Neij, P. Andersen, M. Durstewitz, P. Helby, M. Hoppe-Kilpper, and P.E Morthorst. *Experience curves: A tool for energy policy assessment.* Environmental and Energy Systems Studies, Univ., 2003.

[159] R.R. Nelson. Co-evolution of industry structure, technology and supporting institutions, and the making of comparative advantage. *International Journal of the Economics of Business*, 2(2):171–184, 1995.

[160] R.R. Nelson and S.G. Winter. In search of useful theory of innovation. *Research Policy*, 6(1):36–76, 1977.

[161] R.R. Nelson and S.G. Winter. *An evolutionary theory of economic change.* Belknap Press, 1982.

[162] NetLogo. `http://ccl.northwestern.edu/netlogo/`, Website last visited August 2009.

[163] Cynthia Nikolai and Gregory Madey. Tools of the trade: A survey of various agent based modeling platforms. *Journal of Artificial Societies and Social Simulation*, 12(2):2, 2008.

[164] I. Nikolic. *Co-Evolutionary Method For Modelling Large Scale Socio-Technical Systems Evolution.* PhD thesis, Delft University of Technology, 2009.

[165] Rijkswaterstaat Noordzee. Beschrijving behandeling vergunningaanvragen Wet Beheer Rijkswaterstaatswerken voor windenergie offshore, February 2005.

[166] Noordzeeatlas. `http://www.noordzeeatlas.nl/`, Website last visited February 2013.

[167] Noordzeewind. `http://www.noordzeewind.nl`, Website last visited August 2009.

[168] B. Nooteboom. Innovation, learning and industrial organisation. *Cambridge Journal of Economics*, 23(2), 1999.

[169] B. Nooteboom. Trust as a governance device. *Cultural factors in economic growth*, pages 44–68, 2000.

[170] D.C. North. *Institutions, Institutional Change and Economic Performance.* Cambridge University Press, 1990.

[171] D.C. North. Institutions. *Journal of Economic perspectives*, 5(1):197–112, 1991.

[172] D.C. North. *Institutions, contracts and organisations*, chapter Understanding institutions. University Press, Cambridge, UK, 2000.

[173] D.C. North. Understanding the process of economic change. In *Forum 7: Institutional barriers to economic change: cases considered*, Forum series on the Role of institutions on promoting economic growth. Mercatus Center, George Mason University, 2003.

[174] M. North, G. Conzelmann, V. Koritarov, C. Macal, P. Thimmapuram, and T. Veselka. E-laboratories: agent-based modeling of electricity markets. In *2002 American Power Conference*, pages 15–17, 2002.

[175] M.J. North, N.T. Collier, and J.R. Vos. Experiences Creating Three Implementations of the Repast Agent Modeling Toolkit. In *ACM Transactions on Modeling and Computer Simulation*, volume 16, pages 1–25. ACM New York, USA, January 2006.

[176] Ministry of Economic Affairs. First white paper on energy, 1974.

[177] Ministry of Economic Affairs. Energie en samenleving in 2050, nederland in wereldbeelden, August 2000.

[178] Ministry of Economic Affairs. Energierapport 2002, investeren in energie, keuzes voor de toekomst, 2002.

[179] Ministry of Economic Affairs. Regeling subsidiebedragen Milieukwaliteit Elektriciteitsproductie 2005, 2003.

[180] Ministry of Economic Affairs. Connect 6.000, eindrapportage. Technical report, 2004.

[181] Ministry of Economic Affairs. Energierapport 2008, June 2008.

[182] Ministry of Economic Affairs. Net op zee. Hoofdrapport, February 2009.

[183] Ministry of Economic Affairs. Declaration EU Policy Workshop Development of Offshore Wind Energy, Egmond aan Zee, 30 September and 1 October 2004.

[184] Department of Energy and Climate change. Government Response to Offshore Electricity Transmission, A further Joint Ofgem/DECC Regulatory Policy Update. Final consultation document, 23 March 2009.

[185] Delft University of Technology. Offshore course for professionals. Lecture material, 2009.

[186] Horns Rev offshore wind park. `http://www.hornsrev.dk/`, Website last visited January 2010.

[187] Princess Amalia offshore wind park. `http://www.prinsesamaliawindpark.eu`, Website last visited January 2010.

[188] J. Olthof. as Quality manager at NoordzeeWind, 2005.

[189] United Nations Framework Convention on Climate Change. `http://unfccc.int/kyoto\_protocol/items/2830.php`, Website last visited June 2010.

[190] European Policy Seminar on Offshore Wind Power. Copenhagen strategy on offshore wind power deployment. Copenhagen, Thursday 27 October 2005.

[191] L. Padgham and M. Winikoff. *Developing Intelligent Agent Systems: A Practical Guide*. John Wiley and Sons, June 2004.

[192] Lin Padgham and Michael Winikoff. Prometheus: A methodology for developing intelligent agents. In *Agent-Oriented Software Engineering III*, pages 174–185. 2003.

[193] D. Pellier and H. Fiorino. Assumption-based planning. In *Proceedings of the International Conference on Advances in Intelligence Systems Theory and Applications, Luxemburg*. Citeseer, 2004.

[194] C. Perez. *Globalization, Economic Development and Inequality: An alternative Perspective*, chapter Technological revolutions, paradigm shifts and socio-institutional change, pages 217–242. Edward Elgar, 2004.

[195] Dutch Offshore Wind Energy Converter (DOWEC) project. `http://www.ecn.nl/units/wind/rd-programme/aerodynamics/projects/dowec/`, Website last visited June 2010.

[196] Greater Gabbard Offshore Wind Farm Project. Greater Gabbard Offshore Winds Limited Decommissioning Programme. 577000/403 MGT100 GGR 107, Fluor and Airtricity, 2007.

[197] J. Quist. *Backcasting for a sustainable future: the impact after ten years*. PhD thesis, Delft University of Technology, Delft, 2007.

[198] S. Railsback, S. Lytinen, and S. Jackson. Agent-based simulation platforms: Review and development recommendations. *Simulation*, pages pp609–623, September 2006.

[199] R.P.J.M. Raven. *Strategic niche management for biomass: a comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark*. PhD thesis, Technische Universiteit Eindhoven, 2005.

[200] Mark S. Reed, Anil Graves, Norman Dandy, Helena Posthumus, Klaus Hubacek, Joe Morris, Christina Prell, Claire H. Quinn, and Lindsay C. Stringer. Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, 90(5):1933 – 1949, 2009.

[201] Former British Wind Energy Association RenewableUk. `http:\\www.RenewableUK.com`, Website last visited February 2013.

[202] Repast. `http://repast.sourceforge.net/`, Website last visited August 2009.

[203] Matteo Richiardi, Roberto Leombruni, Nicole J. Saam, and Michele Sonnessa. A common protocol for agent-based social simulation. *Journal of Artificial Societies and Social Simulation*, 9(1).

[204] Rijkswaterstaat. `http://www.rijkswaterstaat.nl`, Website last visited July 2010.

[205] Rijkswaterstaat Dienst Noordzee. Behandeling vergunningsaanvragen Wet Beheer Rijkswaterstaatswerken voor windenergie offshore, Feb 2006.

[206] G. Ringland. *Scenario Planning: Managing for the Future*. 1998.

[207] M.M. Roggenkamp. The regulation of offshore wind parks in the Netherlands. *IELTR*, (8), 2003.

[208] Huub den Rooijen. as Vice President Shell WindEnergy. Interview , 1 December 2005.

[209] A. Rubinstein. *Modeling bounded rationality*. MIT press, 1998.

[210] E.J.W. Sambeek, T.J. Lange, W.J.A. Ruijgrok, and E.A. Pfeiffer. Onrendabele toppen van duurzame elektriciteitsopties. Advies ten behoeve van de vaststelling van de MEP-subsidies voor 2004 en 2005. Technical Report ECN-C–03–085, Energy research Centre of the Netherlands (ECN) and KEMA, 2003.

[211] R.G. Sargent. Verification and validation of simulation models. In *Proceedings of the 37th conference on Winter simulation*, pages 130–143. Winter Simulation Conference, 2005.

[212] Pier-Paolo Saviotti. On the co-evolution of technologies and institutions. In *Towards Environmental Innovation Systems*, pages 9–31. 2005.

[213] F.W. Scharpf. *Games real actors play: Actor-centered institutionalism in policy research*. Westview Pr, 1997.

[214] P. Schaumann and C. Böker. Can jackets and tripods compete with monopiles? *Proc. Copenhagen Offshore Wind*, 5, 2005.

[215] A. Schroeder. Effects of offshore constructions on benthos - Experiences from the research platform FINO1 in the German Bight. Annex 23: Workshop Offshore wind energy: Ecology and Regulation, February 2008.

[216] Peter Schwartz. *The art of the long view: Planning for the future in an uncertain world*. Doubleday Currency, May 1996.

[217] A. Seebregts, M. Scheepers, and H. de Vries. Base load Elektriciteitsprijzen en Brandstofprijzen 2005 tot en met 2020. Technical report, Energy research Centre of the Netherlands (ECN), 2004.

[218] A.J. Seebregts, H.J.M. Snoep, J. van Deurzen, S.M. Lensink, A.J. van der Welle, and W. Wetzels. Brandstofmix elektriciteit 2020; Inventarisatie, mogelijke problemen on oplossingsrichtingen. Technical Report ECN-E–09–046, Energie Centrum Nederland, December 2009.

[219] C.R. Shalizi. *Complex Systems Science in Biomedicine*, chapter 1, Methods and Techniques of Complex Systems Science: An Overview, pages 33–114. New York: Springer, 2006.

[220] S. Shaw, M.J. Cremers, and G. Palmers. Enabling offshore wind developments. *Report produced by 3E in association with EWEA*, 2002.

[221] E. Siemers. After 12 years, vestas loses global market share lead. http://sustainablebusinessoregon.com, February 2012.

[222] SIF Group B.V. `http://www.sif-group.com`, Website last visited August 2010.

[223] H.A. Simon. A behavioral model of rational choice. *The Quarterly Journal of Economics*, 69(1):99–118, 1955.

[224] H.A. Simon. Theories of bounded rationality. Cip working paper nr 66, CIP, March 12 1964.

[225] H.A. Simon. The logic of heuristic decision making. *The logic of decision and action*, pages 1–20, 1967.

[226] M.J. de Smith, M.F. Goodchild, and P. Longley. *Geospatial analysis: a comprehensive guide to principles, techniques and software tools*. Troubador Publishing, 2009.

[227] CBS StatLine. `http://statline.cbs.nl/statweb/`, Website last visited January 2010.

[228] Stichting De Noordzee. Frisse Zeewind 2: visie van de natuur-en milieuorganisatie op de ontwikkeling van windturbineparken offshore, September 2005.

[229] Copenhagen strategy on offshore wind deployment. European policy seminar on offshore wind power. Copenhagen, 27 October 2005.

[230] Student Wave Online study tools Technological Forecasting. `http://www.wiley.com/college/dec/meredith298298/resources/addtopics/addtopic\_s\_02m.html`, Website last visited January 2013.

[231] SWARM. `http://www.swarm.org`, Website last visited August 2009.

[232] J. van der Tempel, W. de Vries, V. Krolis, D. Cerda Salzmann, T. Haverkort, R. Narold, R. van Gilst, H.J. Kooijman, and J. Peeringa. Mangrove findings offshore wind energy in deeper waters. In *EOW Proceedings*, 2007.

[233] PEST template. http://www.businessballs.com/pestanalysisfreetemplate.htm, Website last visited November 2012.

[234] L. Tesfatsion. http://www.econ.iastate.edu/tesfatsi/ace.htm, Website last visited August 2009.

[235] X. Tilburg, J.W. Cleijne, E.A. Pfeiffer, S.M. Lensink, and M. Mozaffarian. Technisch-economische parameters van duurzame elektriciteitsopties in 2008-2009. (ECN-E–07-069 - Versie 2), November 2007.

[236] X. Tilburg, E.A. Pfeiffer, J.W. Cleijne, G.J. Stienstra, and S.M. Lensink. Technisch-economische parameters van duurzame elektriciteitsopties in 2008. Conceptadvies onrendabele topberekeningen. (ECN-E–06-025), February 2007.

[237] Robert Tobias and Carole Hofmann. Evaluation of free Java-libraries for social-scientific agent based simulation. *Journal of Artificial Societies and Social Simulation*, 7(1), 2004.

[238] TenneT TSO. http://www.tennettso.de/site/en/Tasks/offshore, Website last visited November 2012.

[239] TBM TUDelft. http://www.tbm.tudelft.nl/en/about-faculty/departments/multi-actor-systems/systems-engineering/research/projects/group-decision-room/, Website last visited October 2012.

[240] B.C. Ummels. Quick-scan windenergie en opslag: Eindrapport wp1. Report for SenterNovem, the Ministry of Economic Affairs and the Transition platform Sustainable Electricity Supply, TUDelft, December 2007.

[241] B.C. Ummels. *Power system operation with large-scale wind power in liberalised environments*. Utrecht, Labor Grafimedia bv., 2009.

[242] G.J.W. van Bussel. Offshore wind energy, the reliability dilemma. In *Proceedings of the International EWEC Conference*, 2002.

[243] M. Van der Steen, J. Groenewegen, M. Jonker, R. Kunneke, and E.H.M. Mast. *Innovations for a Low Carbon Economy: Economic, Institutional and Management Approaches*, chapter Evolutionary Innovation Systems of Low Carbon Electricity: insights about institutional change and innovation in the case of CHP and Wind Energy, pages 175–202. Edward Elgar Publishers, 2008.

[244] J.W. van Wingerden, A.W. Hulskamp, T. Barlas, B. Marrant, G.A.M. van Kuik, D.P. Molenaar, and M. Verhaegen. On the proof of concept of a 'Smart' wind turbine rotor blade for load alleviation. *Wind Energy*, 11(3):265–280, 2008.

[245] H.E. Veldman and G.H.G. Lagers. *50 Years Offshore*. Penwell Books, January 1967.

[246] A.H. van de Ven and R. Garud. *Evolutionary dynamics of organizations*, chapter The coevolution of Technical and institutional events in the development of an innovation, pages 425–443. Oxford University Press, 1994.

[247] Willem-Jan van der Ven. as Sales manager, Sales Offshore, Vestas, Rheden. Interview , 18 January 2006.

[248] Alpha Ventus. http://www.alpha-ventus.de, Website last visited Sept 2009.

[249] G.P.J. Verbong. Wind power in the netherlands. *Centaurus*, 41(12):137–160, 1999.

[250] G.P.J. Verbong, A. van Selm, R. Knoppers, and R. Raven. *Een kwestie van lange adem - De geschiedenis van duurzame energie in Nederland*. Aeneas, Boxtel, 2001.

[251] A. Verrips, H. de Vries, A. Seebregts, and M. Lijesen. Windenergie op de noordzee, een maatschappelijke kosten-batenanalyse. Technical report, CPB & ECN, 2005.

[252] Vestas. Horns reef work in progress. Press release, 8 July 2004. Randers.

[253] Vestas. `http://www.vestas.com`, Website last visited February 2013.

[254] E. van der Vleuten. *Blackwell Companion to the Philosophy of Technology*, chapter Large Technical Systems, pages 218–223. Wiley-Blackwell, 2009.

[255] Volkskrant. Nederlandse gasvoorraad is eerder op, 21 June 2005.

[256] Centrum voor Publieksparticipatie. `http://www.centrumpp.nl`, Website last visited January 2010.

[257] W. de Vries. as PhD researcher in the We@Sea project, at the TUDelft. Personal communication, 30 August 2010.

[258] Douglas Westwood. Transnational offshore wind supply chain study. Final report, POWER: Pushing Offshore Wind Energy Regions, May 2006.

[259] WI-CDA. Keuzes voor duurzaamheid - energie op de drempel van transitie. Technical report, Wetenschappelijk instituut voor het CDA, 2005. ISBN 90-7449-300-9.

[260] Wikipedia. `http://www.wikipedia.com`, Website last visited November 2012.

[261] U. Wilensky and W. Rand. Making models match: Replicating an agent-based model. *Journal of Artificial Societies and Social Simulation*, 10(4):2, 2007.

[262] Allen Wilhite. Bilateral trade and 'small world' networks. *Computational Economics*, 18(1):49–64, August 2001.

[263] L. Wilkinson. How to build scenarios. *Wired*, 1995.

[264] O.E. Williamson. *Markets and hierarchies, analysis and antitrust implications*. Free Press, 1983.

[265] O.E. Williamson. Transaction cost economics: how it works; where it is headed. *The Economist*, 146(1):23–58, 1998.

[266] O.E. Williamson. The new institutional economics: taking stock, looking ahead. *Journal of economic literature*, 38(3):595–613, 2000.

[267] M. Winikoff and L. Padgham. The Prometheus Methodology. In *Methodologies and Software Engineering for Agent Systems*, pages 217–234. 2004.

[268] Maarten Wolsink. Dutch wind power policy : Stagnating implementation of renewables. *Energy Policy*, 24(12):1079–1088, 1996.

[269] Maarten Wolsink. Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. *Renewable and Sustainable Energy Reviews*, 11(6):1188–1207, 2007.

[270] M. Wooldridge. Agent-based software engineering. *Software Engineering. IEE Proceedings*, 144(1):26–37, Feb. 1997.

[271] M. Wooldridge, N.R. Jennings, et al. Intelligent agents: Theory and practice. *Knowledge engineering review*, 10(2):115–152, 1995.

[272] M.J. Wooldridge. *An introduction to multi-agent systems*. John Wiley & sons Ltd., UK, 2002.

[273] Kinny D. Wooldridge M., Jennings N.R. The Gaia Methodology for Agent-Oriented Analysis and Design. *Autonomous Agents and Multi-Agent Systems*, 3(3):285–312, September 2000.

[274] M.B. Zaaijer. Properties of offshore support structures for large scale wind turbines. In *Proceedings of Offshore Wind Energy Special Topic Conference (CD-rom), Brussel, Belgium*, 2001.

[275] B. Zuidervaart. Er lijkt maar één optie: meer windparken. http://www.trouw.nl, 16 January 2013.

Curriculum Vitae

Eeke Hendrika Maria Mast was born on 28 December 1975 in Hoevelaken, the Netherlands. She attended pre-university education at the Erasmus College in Zoetermeer, where she obtained her diploma in 1994. She went on to Delft University of Technology in the Netherlands to study Applied Mathematics. She obtained her MSc degree in Mathematical Physics in 2003. Her internships were at Risø in Denmark (now DTU-Risø campus), and at the Wind Energy Research Group at the TUDelft. The latter concerned the construction of a vortex model for the estimation of the circulation distribution on a rotor blade from near-wake velocity measurements.

In 2005 she started her PhD at Delft University of Technology, at the Wind Energy section at Aerospace Engineering, combined with the Economics of Infrastructures section at the department of Technology, Policy and Management. The PhD work was a part of the PhD@sea project in We@Sea. During her time there she gave presentations at conferences and to master students, she organised a group decision room workshop with stakeholders and supervised MSc students.

In September 2011 Eeke joined Garrad Hassan, an international energy advisory group, as an offshore engineer in the Offshore Wind Practice group. Her work there mainly entails cost modelling for conceptual comparative studies, as well as assistance in due diligence, regulatory studies and market studies. After a merger with GL and later with DNV, Garrad Hassan was renamed to DNV GL Energy.

Eeke lives together with her partner Frans and together they have a daughter Lika and a son Samuel.