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# INVESTMENT COSTS OF OFFSHORE WIND TURBINES

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# Contents

# Abstract

The use of renewable energies for electricity generation is necessary to reach the US government goals for reducing their $CO_2$ emissions. One of the key technologies is wind energy. It is an abundant resource with a high potential for net energy generation, especially offshore. Until now, the US hasn't experience in offshore wind technology. The state of Michigan, surrounded by the Great Lakes offers a very high potential for offshore wind generation.

Therefore the School of Natural Resources and Environment (SNRE) at the University of Michigan is working on a project to analyze the wind energy potential in Lake Michigan. A combination of cost analysis and GIS Mapping show those locations in the Lake, where the levelized costs of energy (LCOE) are be at least.

For different offshore locations with certain water depths and distances to shore, different types of foundation are preferred to use. The choice of foundation is mainly dependent on water depth.

The aim of my research is to figure out the total investment costs of offshore wind turbines with different types of foundations. In addition a separation in foundation-, turbine- and electrical costs is done. The aim is to create a graph of investment costs of all foundation types according to water depth respectively distance to shore.

# Methodology

This chapter explains the methodology and approach for my research.

First I split up the whole investment costs into foundation, turbine and electrical costs. I separate between four different types of foundations: Monopile, Gravity base, Tripod and Floating. Then I break down several foundations costs into production, transport and installation costs. You can see it in the schema in Fig. 1 .

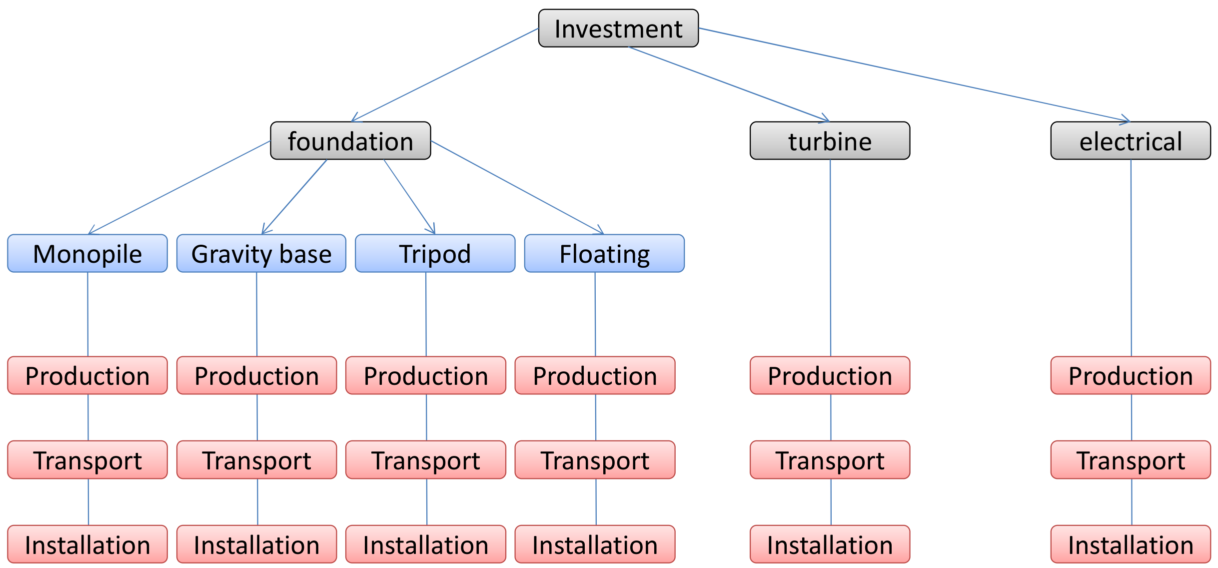


**Fig. 1: Schema of the used methodology**

The next step is to find sources, which gives information about investment costs for each foundation type. In Consideration are both scientific articles (with giving equations) and cost data from past projects.

After collecting the data, the values are converted into USD and then inflated from the data collecting year into the year 2014. In case of published equations in scientific articles, the values are converted and inflated as well and plotted in excel for several water depths.

Beyond a selection of equations and data points is done, so that a trendline can be added finally. This trendline gives an average of all equations and data points, which are in consideration. The selection process is being affected by additional criteria like data collecting year or relevance for the Michigan "Great Lakes area".

Furthermore a final equation for all types of foundations is created and the total investment costs for several water depths get compared to data from the database. For analyzing the data, programs like Excel and Matlab are used.

At the end a graph with total investment costs for different types of foundation according to water depth respectively distance to shore is created. The calculated investment costs get compared with the collected data from past projects. At the end the levelized cost of energy (LCOE) is calculated and compared with recent published data from DOE and NREL.

## Collect data

The first step for research and cost analysis is collecting data. Finding certain cost data for different types of foundation is very difficult, because of:

- lack of information in published data
- the suppliers of those technologies does not want to publish their data, because the whole industry sector is defined by a high standard of knowledge and competition

Hence a lot of cost data comes from scientific articles, online databases and governmental reports. In Tab. 8 in the appendix you can see which data sources are being used.

There is a lot of investment cost data published about Monopile foundations, because the experience in building offshore wind turbines with this foundation technology is very high. In contrast to that, less data about other types of foundation is provided. Those circumstances make it quite difficult to create a cost model equation for every foundation type.

Getting cost data of offshore wind turbine foundations one approach is to contact manufactures individually. There are a few manufactures in Europe, which produced offshore foundations for Germany, Denmark and the UK in the past (see Tab. 1). I have contacted 6 of them and I got 3 answers, that they cannot provide this data for me.

| **manufacturer** | **kind of foundation** |
|---|---|
| | |
| Ambau | Tripod |
| Ramboll | Monopile |
| Aker Solutions | Tripod |
| Trianel | Tripod, Monopile |
| C-Power | Gravity Base |
| Weser Wind | Tripod |
| Bilfinger Berger | Monopile |
| Hochtief Construction | Gravity Base |

**Tab. 1: manufacturers of offshore wind turbine foundations**

Another really good resource in terms of collecting investment cost data of past wind turbine projects is the database “4coffshore.com”. It is an independent marine energy consultancy from Great Britain, which collects and provides several data about Offshore Wind Farms. The database provides detailed investment costs as well as commissioning dates etc.

Basically the used sources can be divided into equations and data points.

## Equations

The majority of the equations come from scientific articles, which are published online by "sciencedirect.com". Mostly the equations are given in a specific unit, like EUR per MW capacity. Nearly all equations have a significant influence on water depth. The Monopile investment cost equation, published by Nielsen takes also certain constant wind turbine parameters into account. All equations are going to collect with a data collecting date and a publishing date, so that the values could easily transpose and inflate to 2014 USD.

## Data points

I have found data about investment costs of Monopile foundations at certain water depths. There is a data set of three data points, which is based on data from past projects and another data set with five predicted data points of projects, which might be realized in the future.

The values for the past projects come from a report of Gooch: "An Energy and Cost Based GIS Approach to Offshore Wind Farm Site Mapping" from 2012. It includes the wind farms "Liverpool Burbo Bank" in Great Britain, "Arklow" in Ireland and "Horns Rev + Nysted" in Denmark.

The predicted values are based on a Seawind case study from 2001, which takes different offshore wind turbine locations in Ireland, France, Spain, Great Britain and Germany into account.

## Currency / Exchange

After collecting the investment costs in the national currency, the values need to be converted and inflated to 2014 USD. In a first step the values get converted into USD in the data collecting year. For that an online foreign exchange service is used [http://www.usforex.com/forex-tools/historical-rate-tools/yearly-average-rates]. British Pound (GBP), Euro, Norwegian Kroner (NOK) and Swedish Krona (SEK) have to be converted. In Tab. 9 in the appendix you can see the conversion factors for each currency.

In a second step all values get inflated from the data collecting year into the year 2014. The online CPI Inflation Calculator is used [http://data.bls.gov/cgi-bin/cpicalc.pl]. The inflation values are attached in the appendix, too.

# Assumptions

During the research a few assumptions are made. In consideration is a 3 MW turbine from Vestas (V90) with a rotor diameter of 90 m. The whole wind farm consists of 100 turbines with 10 turbines in a row.

The distance between each wind turbine must be at least seven times the rotor diameter, which means 630 m by use of a V90 wind turbine. The cable length between each wind turbine is at least 830 m. All wind turbines in a row could be connected with a 7 Km connection cable to the offshore substation.

Those assumptions are based on NREL's paper "Electrical Collection and Transmission Systems for Offshore Wind Power" from 2007.

# Research

## Foundations

As mentioned above, in consideration are four different types of foundations for offshore wind farms: Monopile, Gravity base, Tripod and Floating. Each foundation type can be used for a certain water depth. Several studies to application of offshore foundations according to water depth were already done. They base on operating experience, simulation and calculations.

The application of Gravity base foundations is common between 1 m – 20 m. In a water depth range between 1 m – 30 m mostly Monopile foundations were used. Tripod foundations are a transition technology between shallow and deep water (20 m – 50 m). In water depths higher than 50 m only floating foundations are going to be used. You can see the application of offshore foundations according to water depth in Tab. 2.

**Tab. 2: application of offshore foundations according to water depth**

| concept | 1 m | 10 m | 20 m | 30 m | 40 m | >50 m |
|---|---|---|---|---|---|---|
| | | | | | | |
| Gravity base | X | X | X | | | |
| Monopile | X | X | X | X | | |
| Tripod | | | X | X | X | X |
| Floating | | | | | | X |

### Monopile

With the collected investment costs of monopile foundations, both equations and data points, it is possible to plot those data in Excel. In terms of comparability it is useful to create the graph on a 2014$/MW basis. The spec. investment cost of a Monopile foundation is on the vertical axis in Millions, while the horizontal axis presents the water depth. The influence of water depth for the foundation investment costs is higher than the influence of distance to shore. That is why most equations for investment costs are only dependent on water depth.

You could see the results in Figure 1.

The graph shows the specific investment costs of Monopile foundations in 2014$/MW according to water depth. It includes data points and lines. The data points are both values from existing projects and values of planned projects, where a cost estimate in a case study was done. The lines are based on equations, which are plotted in excel. There are three lines, which are only valid in a certain range (e.g. from 20m – 30m). In this range the specific Monopile investment costs are constant. Most of the given equations are linear with differences in their incline. One line is based on an exponential equation [Gooch].

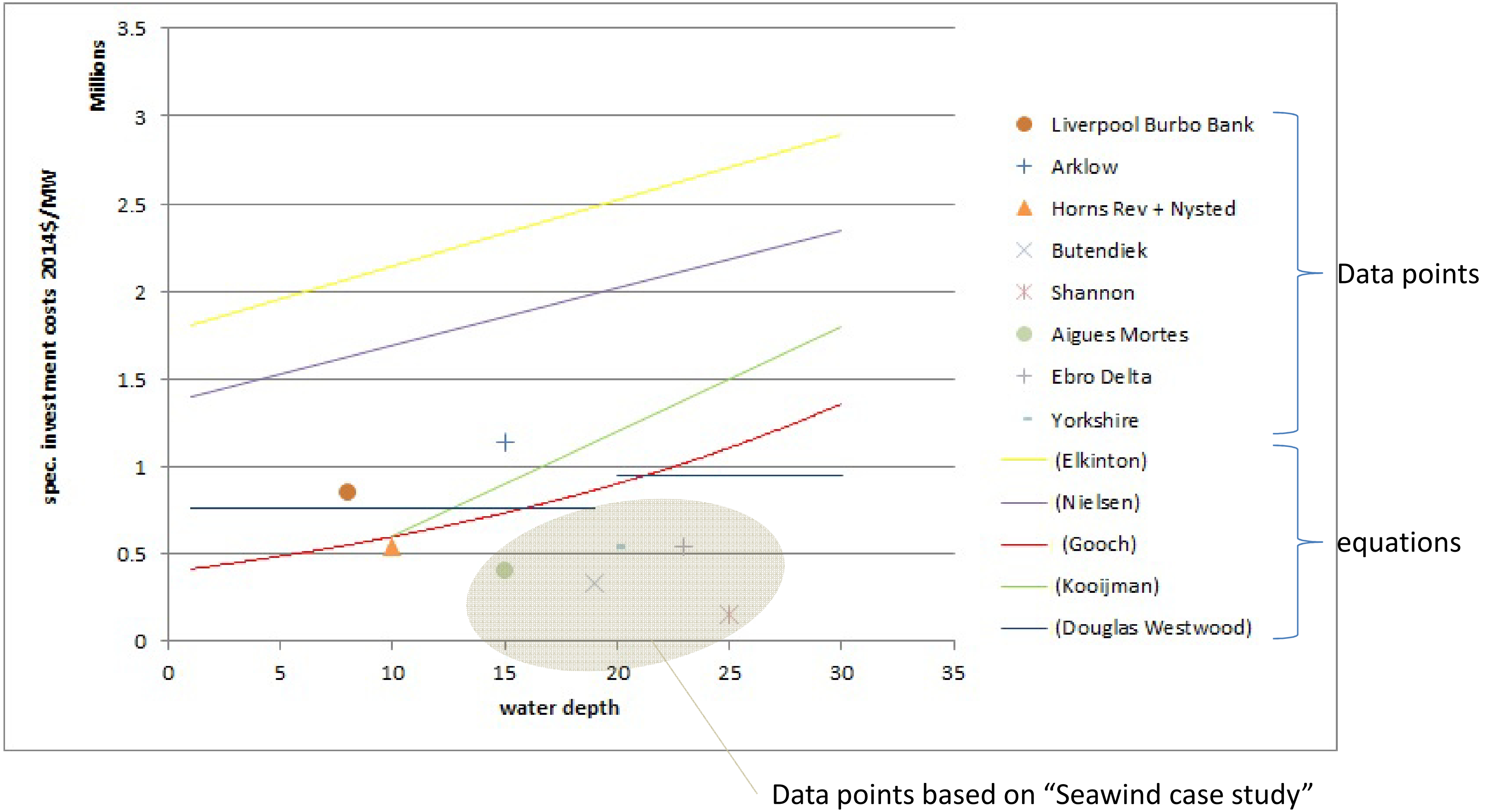


Figure 1: spec. Monopile investment costs [$/MW] according to water depth

Below I give additional information and explanations to the used equations and plotted lines.

The line with the highest spec. investment costs (yellow color) is based on an equation from Elkinton, published in the project report “Offshore Wind Farm Layout Optimization (OWFLO) Project. An Introduction”, which is basically based on an own developed cost model. For his cost model he uses the data from three existing wind farms: Horns Rev, Arklow and Mittelgrunden. Elkinton worked as a Research Assistant for the Renewable Energy Research Lab at the University of Massachusetts. Now he is the Technical Leader for North America Offshore projects by DNV GL (Garrad Hassan).

The line with the second highest spec. investment costs (purple line) is based on an equation from Nielsen. His equation is based on a model, which he creates with data from past wind farm projects in Denmark. He published his results in “Offshore wind energy projects feasibility study guidelines. Seawind altener project 4.1030/Z/01 – 103/2001” in 2003.

Goochs equation is based on data from the “Town of Babylon Accounting Company”. His exponential equation is empirical and is created by extrapolating sums of foundation production and installation costs for different depths.

Kooijman published in 2008 a diagram about total investment costs for a Monopile foundation of a 2.5 MW wind turbine in the Dutch part of the North Sea. The line is presented in green color in the diagram.

Douglas Westwood is an employee-owned company and the leading provider of energy business strategy, research and commercial due-diligence services. The foundation costs are based on own research and data provided by turbine manufactures. The equation is an average of recently installed and soon to be installed projects in the North- and Norwegian Sea.

The two data points “Liverpool Burbo Bank” and “Arklow” are specific Monopile foundation investment costs of realized projects. The data is based on Gooch’s “An Energy and Cost Based GIS Approach to Offshore Wind Farm Site Mapping” [2012].

The wind farm “Liverpool Burbo Bank” is 7 Km offshore in the Irish Sea located. It consists of 25 wind turbines with 3.6 MW capacity each. It was commissioned in 2007 in shallow water conditions (8 m).

The wind farm “Arklow” is a wind farm with a total capacity of 25 MW. It was commissioned in 2004, 11.6 Km from the Irish coast in 15 m deep water.

The data point “Horns Rev + Nysted” is an average of Monopile investment cost for the wind farms Horns Rev and Nysted in Denmark. The wind turbines at Horns Rev are built 18 Km offshore in 10 m water depth on Monopile foundations, while the Nysted wind turbines are built on gravity based foundations in 8 m water depth. Both wind farms have a total capacity of 160 MW. The investment cost data is collected from Risoe DTU, Technical University of Denmark.

The five framed data points are cost estimates made by EMD from the year 2012 for a case study and are based on knowledge from existing onshore wind farms combined with Denmarks first offshore wind farms. EMD is a Danish software and consultancy company supplying countries worldwide with software and consultancy services within the field of project design, planning and documentation of environmental friendly energy projects, particularly wind energy projects.

The case study was published under “Offshore wind Energy Projects Feasibility Study Guidelines Seawind” as part of the Altener Project 4.1030/Z/01-103/2001. Some of the analyzed projects are realized until now, but for higher investment costs than estimated. Some of them are in the planning phase and some are not going to realize in the future.

Below I explain shortly, where the wind farms should be located, which capacity they should have and if they are built meanwhile.

“Butendiek” is one of the wind farms with the highest capacity (400 MW), 33 Km off the North Sea coast located and powered by 3.6 MW turbines. This project was commissioned in 2014 in Germany.

“Shannon” is a smaller wind farm with 8 turbines and a total capacity of 40 MW, 1.5 Km offshore in 25 m deep water. It was built 2014.

“Yorkshire” is under construction 10 Km off the UK coast, using 3 MW turbines with a total capacity of 219 MW.

The other projects “Aigues Mortes” and “Ebro Delta” does not exist yet. “Aigues Mortes” should be located 4 Km from the French coast in the Mediterranean Sea with a water depth of 15 m and “Ebro Delta” with a total capacity of 432 MW in the Balearic Sea in Spain.

### *Analysis*

As you could see in Figure 1 the investment costs based on the equations are in a range from 0.5 - 3 Mill $/MW dependent on water depth. The predicted investment costs for the wind farms from Seawind case study are between 0.15 – 0.54 Mill $/MW. The values based on the case study are much lower than the actual data points of past projects. But this circumstance reflects the trend of predicted and actual costs.

A trendline for monopile investment costs based on the given equations and data points can be added. The result without the five predicted data points is shown in Fig. 2. The result with the predicted data points is attached under Fig. 13 in the appendix. The difference between the two plots is minimal, only the slope of the trendline is changing negligible.

Based on this plot, the following equation is used for specific Monopile investment costs:

$$C_t = 986{,}059 * \exp(0.0182 * x) \quad [\$/MW] \qquad \text{(eq. 1)}$$

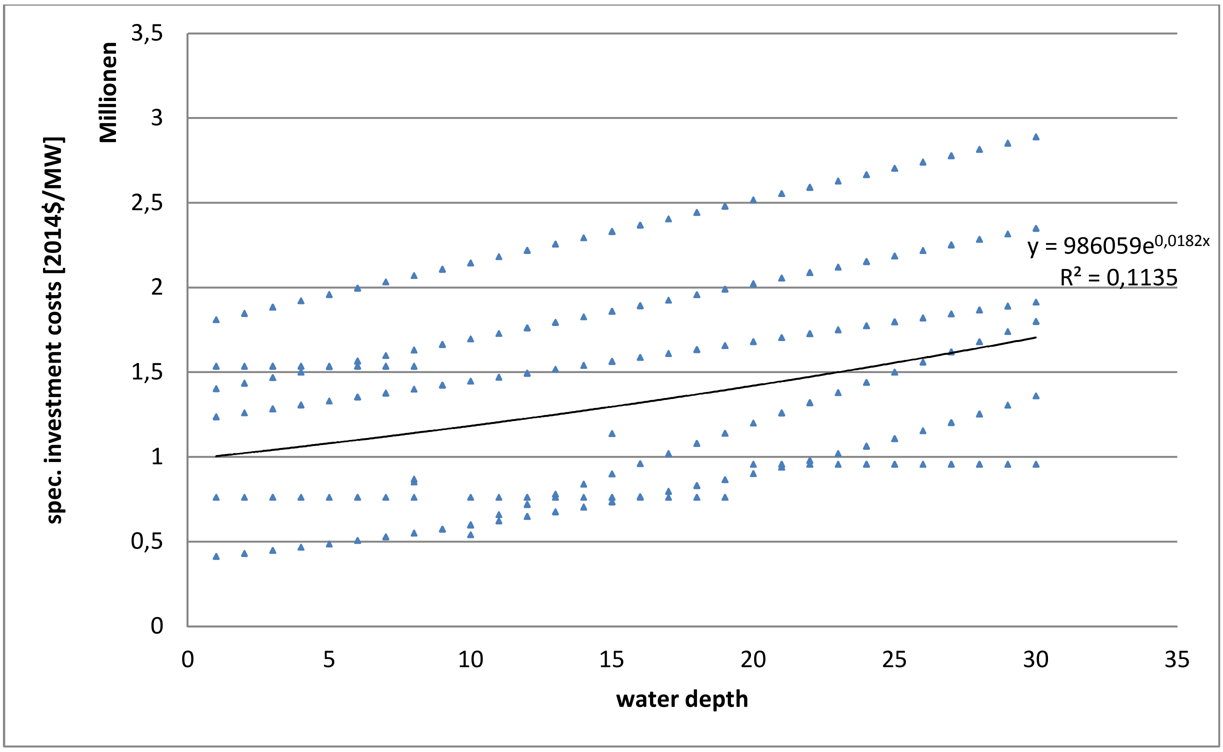


**Fig. 2: Trendline for Monopile investment costs according to water depth based on equations and data points from past projects**

## Gravity Base

The cost analysis of gravity based foundations (GBS) is influenced by a lack of information. In Europe, especially in Belgium and the Netherlands, there are a few wind turbines built on gravity based foundations. But the Operators cannot provide certain investment cost data.

The only source I could find is a diagram in speech slides from Ballast Nedam, a concrete offshore foundation manufacturer. This diagram shows i.a. the GBS investment costs according to distance to shore for a 5 MW and an 8.5 MW wind turbine. The investment cost for a concrete GBS with 5 MW is about 2.5 - 3 Mill Euro2009 and for the 8.5 MW version about 3.75 - 4.1 Mill Euro2009. As you could see in Fig. 3 the influence of distance to shore to the total investment costs is low. Based on those two lines, an equation of specific GBS investment costs [in $2014/MW] according to distance to shore is created. It is presented below.

$$ct = 278.34 * dshore + 814{,}403.8 \quad [\$/MW] \qquad \text{(eq. 2)}$$

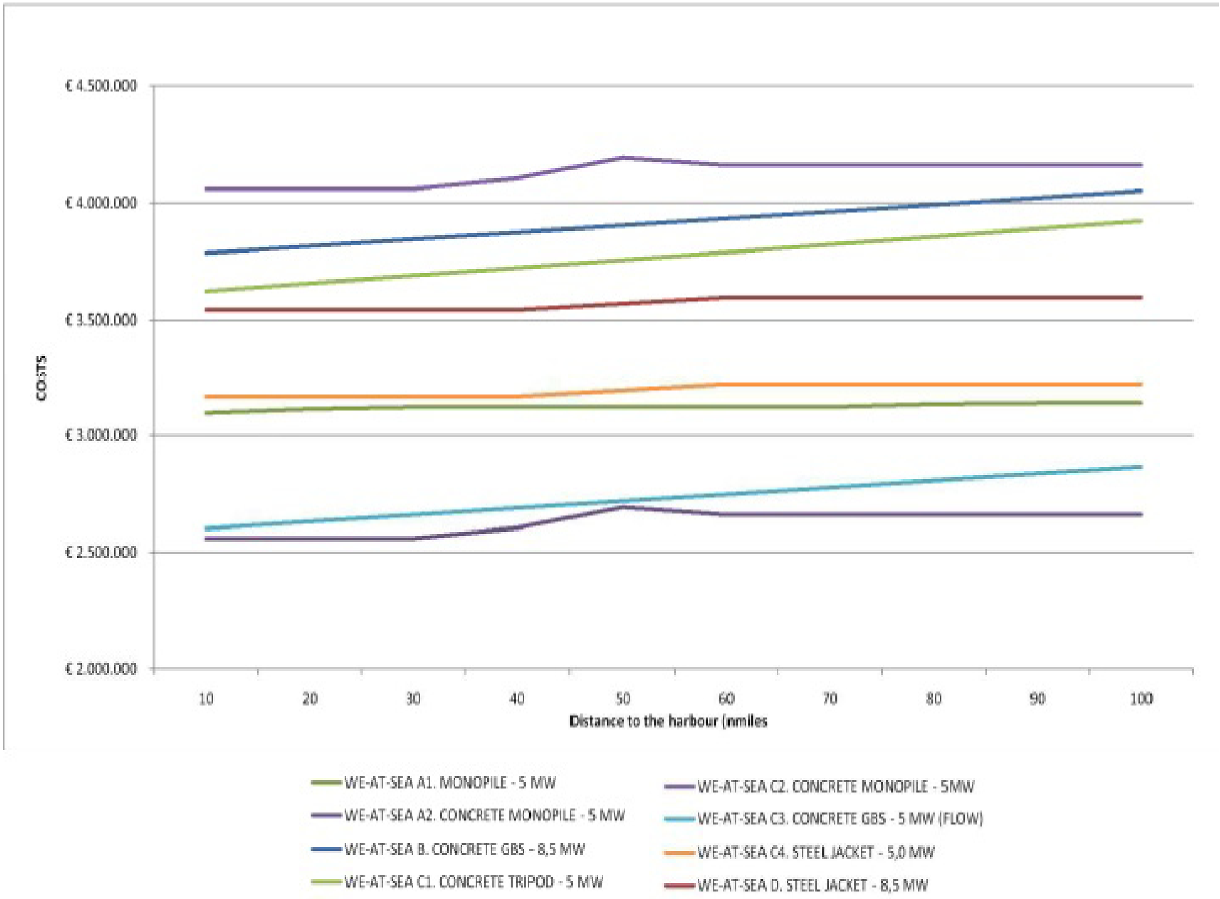


**Fig. 3: Total investment costs [Euro2009] for several GBS concrete foundations according to distance to shore based on talk slides from Ballast Nedam**

Investment cost data from a second source, which is based on a self installation concept for a 5 MW turbine from MonobaseWind is with six times higher investment cost as "normal" not representative for GBS foundations. Nevertheless this concept from 2011 is still in the development phase.

### *Analysis*

Even for a GBS foundation, as well as for a Monopile and Tripod foundation, the dominant factor in terms of investment costs is water depth. The influence of water depth is much greater, than the influence on distance to shore. Unfortunately this fact cannot be displayed in my equation.

## Tripod

The lack of information getting useful cost data about Tripod investment costs is very high. The only useful source is the diagram from the Ballast Nedam speech slides, which I have used already for the GBS foundation investment costs. As you can see in Fig. 3 a 5 MW concrete Tripod foundation is assumed, but in the cost analysis we want to take a steel Tripod foundation in consideration. Additional, the equation is only dependent on distance to shore, while the influence of water depth might have a greater impact on the costs. That means that the equation is not exact and might decrease the actual investment costs for a steel Tripod.

$$ct = 459.72 * \mathrm{dshore} + 1,104,771 \ \ [\$/\mathrm{MW}] \qquad \text{(eq. 3)}$$

### Floating

For analyzing the investment costs of floating foundations, I am using three sources:

- Myhr. “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective” [2014]
- Borgen. “Floating Wind Power in Deep Water - Competitive with Shallow-water Wind Farms?” [2010]
- Nikolaos. ”Deep water offshore wind technologies” [2004].

Fig. 4 shows the total investment costs in Euro/MW for different Floating foundation concepts based on data from Myhr [2014]. The concepts TLB B, TLWT and TLB X3 are tension-leg concepts. Tension-leg is the cheapest floating concept and consists basically of a floating platform, which is moored and anchored with chains to the sea bottom.

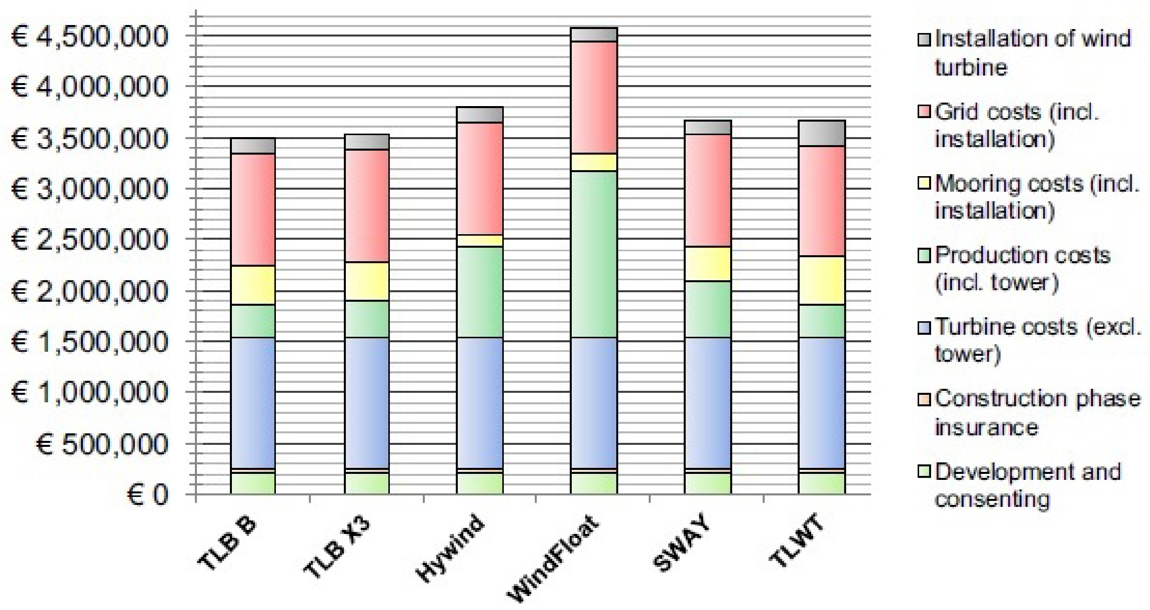


Fig. 4: Specific total Investment costs [Euro/MW] for different Floating foundation concepts by Myhr [2014]

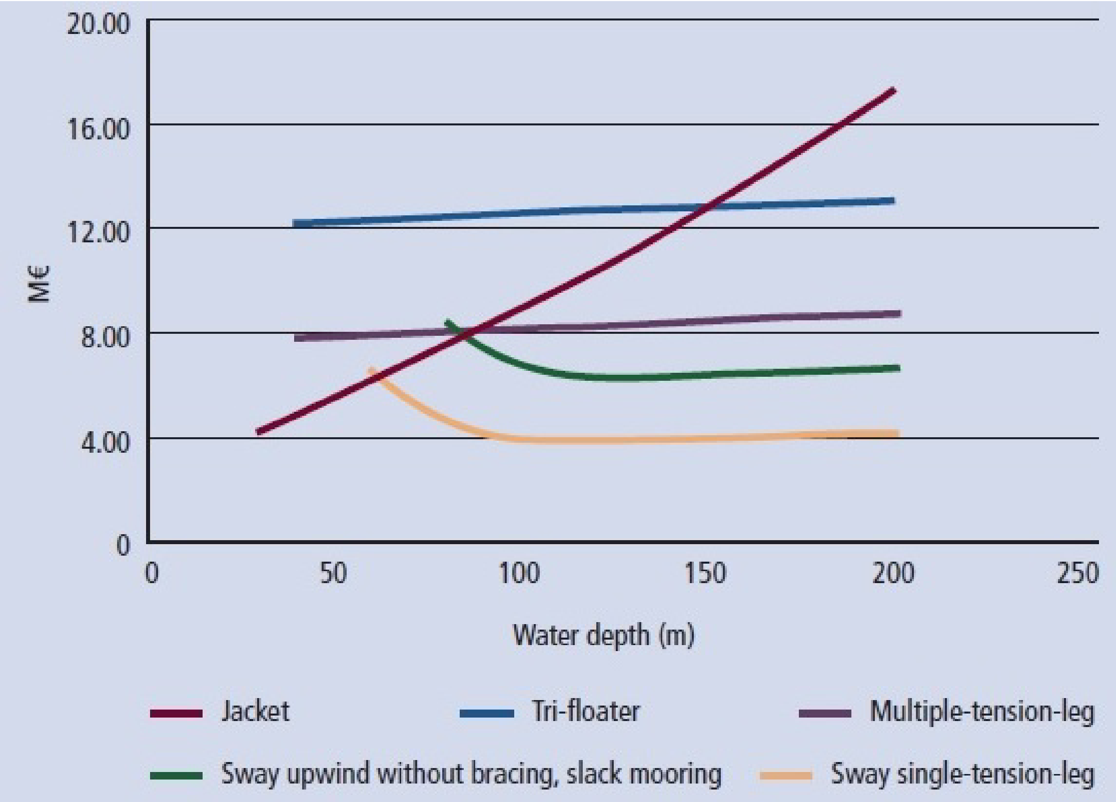


**Fig. 5: Total Investment costs [Mill 2010 Euro] for different Floating foundation concepts (5 MW) compared to Jacket foundation by Borgen [2010]**

Fig. 5 presents the total investment costs in Mill 2010 Euros for different floating foundations concepts on a 5 MW basis. Presented are three tensions-leg concepts with total investment costs in a range from 4 – 9 Mill 2010 Euros and a Tri-floater concept with about 12 Mill 2010 Euros. For comparison, how the investment costs of “traditional” foundations increase with water depth, a line for a jacket foundation is in that diagram too.

After consulting with Amy Chiang only tension-leg concepts are in consideration for this research.

At the moment, there are only a few existing showcase projects of floating foundations in Europe and Japan. The experience in using those foundations is very low and still in the development phase. Because of that, the published cost data in scientific articles and reports is mostly based on estimates and predictions. Especially the published cost data from Borgen [2010] for several floating concepts have to handle with care.

### *Analyse*

The analysis of the given cost data shows, that the investment costs for tension-leg concepts are between 3.4 – 11.6 Mill $/MW (compare Fig. 6). Such a big gap between investment costs indicates a new technology and shows that even the specialists are unsure about the upcoming price trend. As I mentioned, the floating technology is still in the development phase.

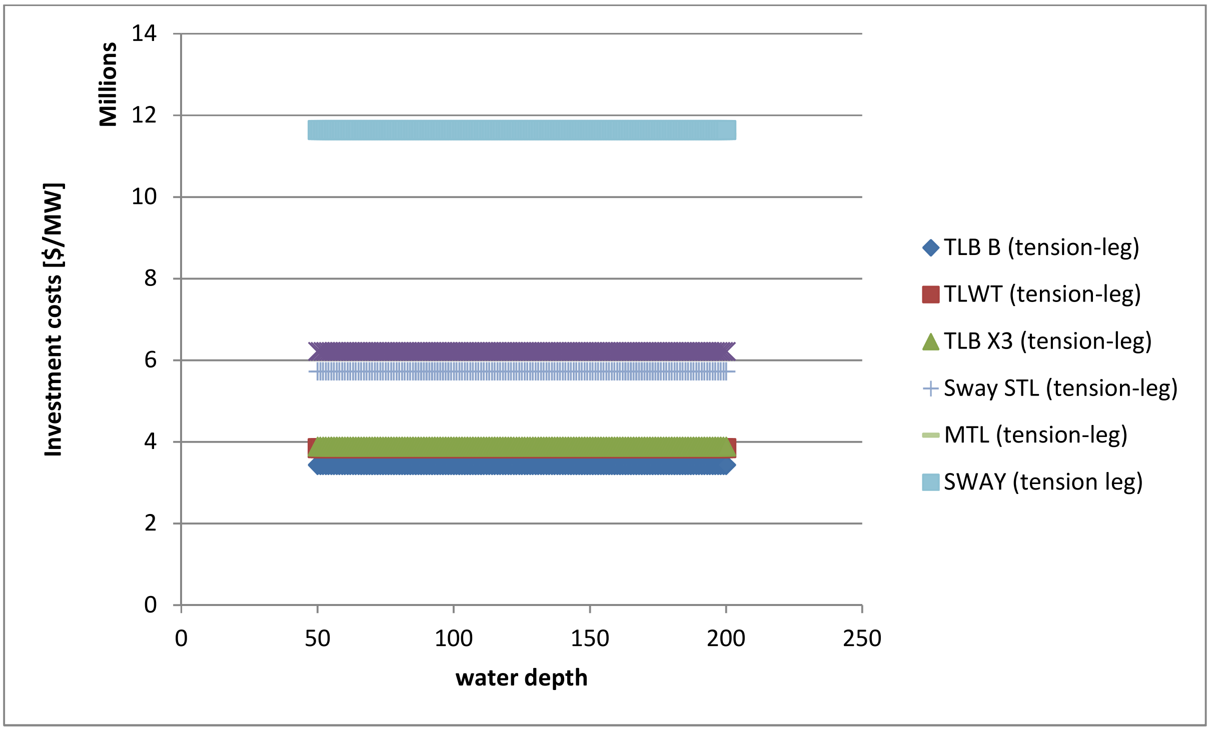


**Fig. 6: Investment costs [Mill $/MW] of tension-leg floating foundations based on data from Myhr, Borgen and Nikolaos**

An average investment cost for a floating foundation would be around 7 Mill $/MW. The floating foundation is the only foundation, which is generally not dependent on water depth. With higher water depths, the costs for chains and anchors increase, but this cost is compared to the rest of the costs negligible.

## Turbine

The turbine investment costs are divided into production, transport and installation costs. In consideration are 12 sources with different data collecting years. Some of them split up several costs and some sources give the total investment costs of the turbine. The values are originally assumed for a 3 MW turbine, but they are calculated on a per MW basis. In Tab. 3 you can see the investment costs of a 3 MW wind turbine (WT) based on different sources.

Turbine investment costs are not varying that strong, so that you could nearly assume them as constant. Averaging the values shows total turbine investment costs of 1.8 Mill$/MW.

Tab. 3: Total turbine investment costs for a 3 MW WT based on different sources

| concept / source | Total investment costs for a turbine [2014$] |
|---|---:|
| M. Dicorato | 4431345.693 |
| Gooch | 3073352.417 |
| EWEA | 3619719.423 |
| Douglas-Westwood | 6887886.918 |
| Ernst & Young | 7819143.03 |
| Nikolaos | 7696839.754 |
| Risoe DTU | 3780792.663 |
| Roland Berger | 5486986.292 |
| NREL | 5850030 |

## Electrical Infrastructure

For the electrical infrastructure cost analysis I am using 11 sources, which providing investment costs for production, transport and installation.

You need inter array and transmission cables to connect an offshore wind farm with the grid. Inter array cables connect the turbines offshore among each other and have a cross-section area of 240 - 630 $mm^2$, while transmission cables with a cross-section area of 1600 $mm^2$ connecting the substations to each other [NREL: "Electrical Collection and Transmission Systems for Offshore Wind Power", 2007]. In the Literature you can find different investment costs for those cables (compare Tab. 4). The prices for those cables are high dependent on the copper price on the market.

Tab. 4: Electrical Cables and their specific production investment costs [$/Km]

| **Electrical Cables** | **Investment cost [$/Km]** | **source** | **Data collecting year** |
|---|---|---|---|
| Inter array cable 240 $mm^2$ | 247,800 $/Km | Douglas – Westwood | 2009 |
| Inter array cable 630 $mm^2$ | 672,600 $/Km | Douglas – Westwood | 2009 |
| Inter array cable | 380,755 $/Km | Myhr | 2013 |
| Inter array cable | 174,048 $/Km | Nikolaos | 2004 |
| Inter array cable | 708,000 $/Km | NREL | 2006 |
| Inter array cable | 624,000 $/Km | DTI | 2007 |
| | | | |
| Transmission cable 1600 $mm^2$ | 584,100 $/Km | Douglas - Westwood | 2009 |
| Transmission HVDC cable | 600,265 $/Km | Myhr | 2013 |
| Transmission cable | 784,000 $/Km | Nikolaos | 2004 |
| Transmission cable | 967,600 $/Km | NREL | 2006 |

Besides the cables, other electrical equipment is necessary. It is listed below in Tab. 5. Dependent on the total capacity, one offshore substation per wind farm is sufficient, normally.

Tab. 5: Specific production investment cost [$/MW] of additional electrical equipment for an offshore wind farm

| Electrical infrastructure equipment | Investment cost | source | Data collecting year |
|---|---|---|---|
| Offshore Substation | 47,040 $/MW | Nikolaos | 2004 |
| Offshore Substation | 16,520 $/MW | NREL | 2006 |
| Offshore Substation | 343,380 $/MW | Douglas - Westwood | 2009 |
| Offshore Substation | 400,000 $/MW | Myhr | 2013 |
| | | | |
| | | | |
| Onshore Substation | 11,800 $/MW | NREL | 2006 |
| Wind turbine transformer | 59,590 $/WT | NREL | 2006 |

There might be a trend to higher investment costs of offshore substations the more recent the collected data is. I think the fact that they are using new materials for manufacturing substations plays here an important role.

Based on NREL's paper "Electrical Collection and Transmission Systems for Offshore Wind Power" from 2007 the transportation costs via freighter are about 82.6$/$m_{cable}$. But this value seems to be negligible in comparison to production and installation of the electrical infrastructure.

The installation costs of the electrical equipment are listed in Tab. 6.

Tab. 6: Installation costs of electrical equipment

| Electrical equipment | Installation costs | source | Data collecting year |
|---|---|---|---|
| Inter array cable | 177,000 $/Km | Douglas-Westwood | 2009 |
| Transmission cable | 531,000 $/Km | Douglas-Westwood | 2009 |
| Substation | 67,260 $/MW | Douglas-Westwood | 2009 |

The calculations on a per MW basis including constant and variable costs of producing, transport and installation of electrical infrastructure give the following equation according to distance to shore:

$$\mathbf{C_e = 442{,}483.33 + 7{,}236 * dshore\ [\$/MW]} \qquad \text{(eq. 4)}$$

## Total investment costs

Finally I am able to sum up all single investment costs to a total investment cost for the whole wind farm on a per MW basis. The total investment cost of the wind farm includes the costs for the used foundation, turbine and electrical infrastructure costs.

The following values and equations are on a per MW basis and show the total investment costs according to water depth, respectively distance to shore for Monopile, Gravity base, Tripod and Floating technologies.

**Monopile: 2,242,483.33 + 7,236*$d_{shore}$ + 986,059*exp(0.0182*D)**

**Gravity Base: 3,056,887.13 + 7,514.34*$d_{shore}$**

**Tripod: 3,347,254.33 + 7,695.72*$d_{shore}$**

**Floating: 5,820,907 + 7,236*$d_{shore}$**

Making those values comparable to others from the Literature (mostly named as ICC costs) Planning & Development costs needs to be added. Recent Literature assumes around 10% of the total investment costs for Planning & Development.

## Create diagrams based on total investment costs

After sum up the total investment costs for each foundation type it is possible to create separate diagrams dependent on water depth and dependent on distance to shore based on own equations.

Normally all equations for different types of foundation should be dependent on water depth and distance to shore. Because of lack of information only the Monopile equation is based on both variables. In order to create diagrams Excel and Matlab are going to be used. Excel is able to create diagrams, which are dependent on one variable, while Matlab is able to create 3D-surfaces dependent on two variables.

The result of plotting the equations for different types of foundations in excel can be seen in Fig. 7 and Fig. 8. Fig. 7 presents the specific investment costs [$/MW] for all kind of foundations according to water depth. The variable “distance to shore” must be holding constant in order to plot the investment costs according to water depth. The following assumptions for “distance to shore” are made:

- Monopile: 30 Km
- GBF: 25 Km
- Tripod: 50 Km
- Floating: 70 Km

The assumptions are based on average values for “distance to shore” from past projects for every kind of foundation.

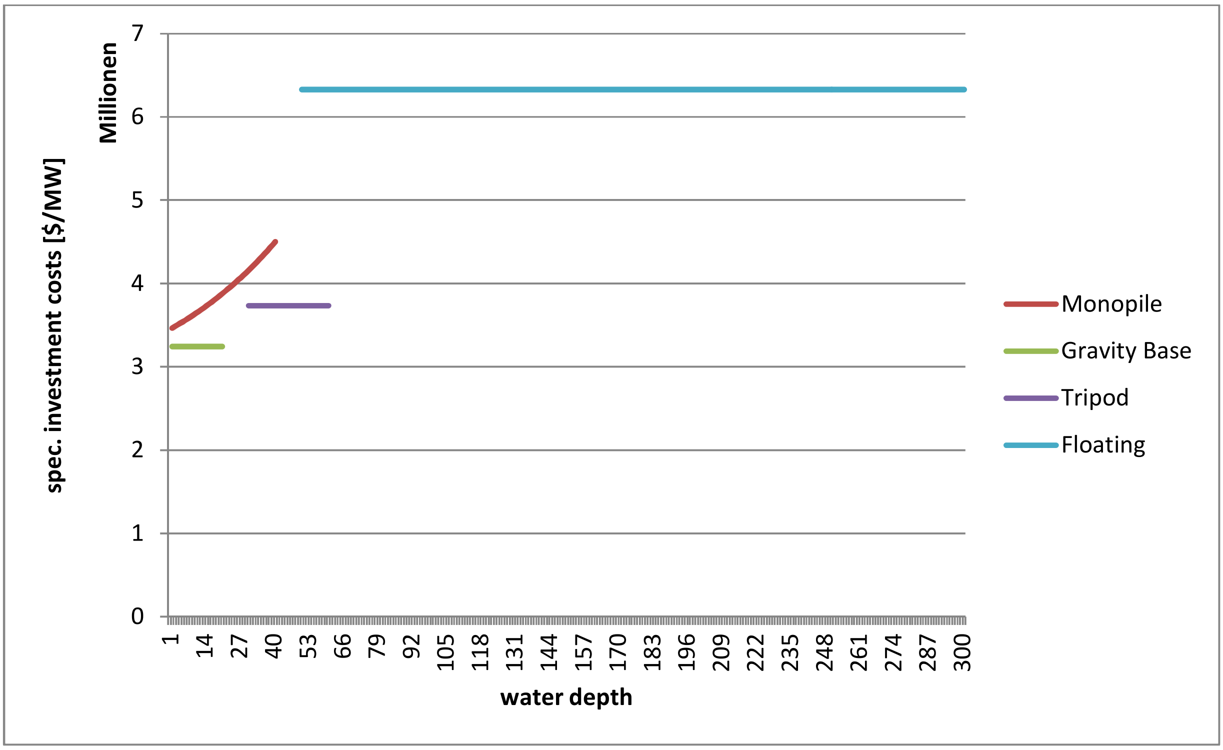


**Fig. 7: specific investment costs [$/MW] for different types of foundations according to water depth**

Fig. 8 presents the specific investment costs [$/MW] for all kind of foundations according to distance to shore. The variable "water depth" must be holding constant in order to plot the investment costs according to "distance to shore". The following assumption for "water depth" is made:

- Monopile: 25 m

The assumption is based on an average value for "water depth" from past projects for Monopile foundations. Assumptions for other kind of foundations are not necessary, because they are not dependent on water depth.

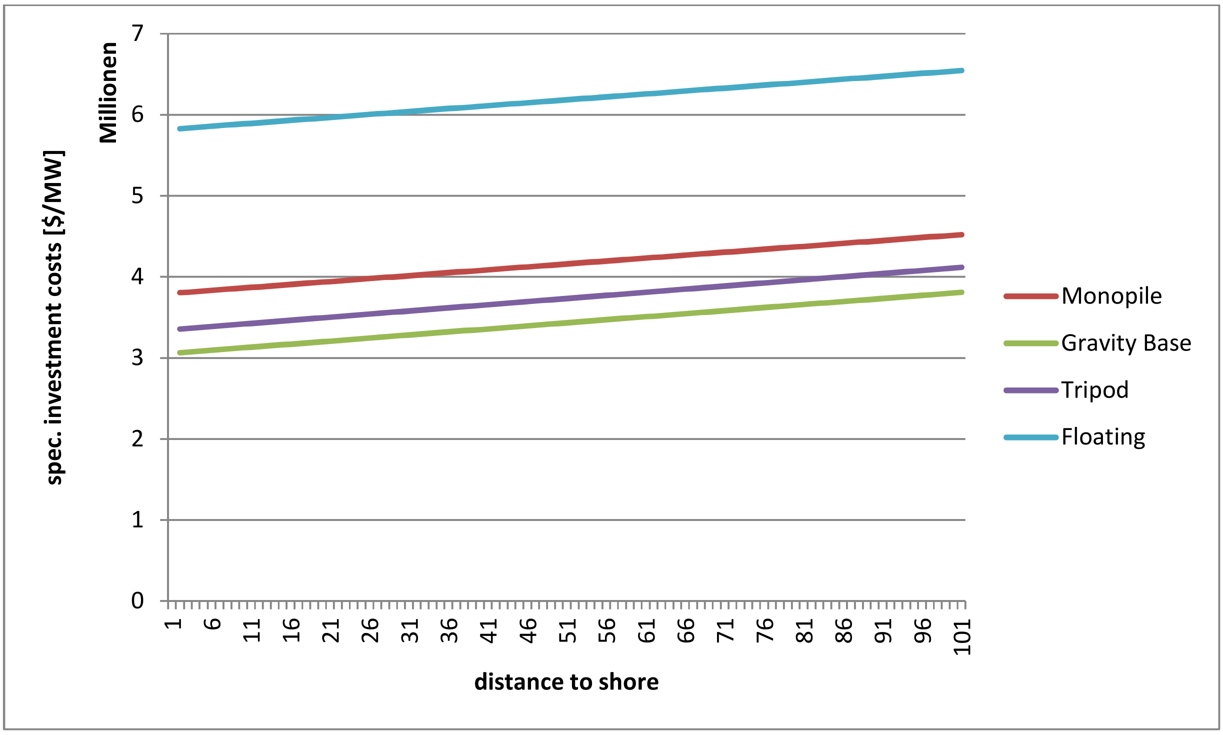


Fig. 8: specific investment costs [$/MW] for different types of foundations according to distance to shore

The result for plotting the Monopile equation according to water depth and distance to shore in Matlab is shown in Figure 2. The created surface shows, that the investment cost increase with higher water depth as well as with higher distance to shore. The slope on the "water depth side" is greater than the slope on the "distance to shore side", which indicates a higher influence of water depth for the total investment costs.

## Create a database

Another key factor of the research is to create a database, which includes investment cost data from past wind turbine projects (see Figure 3). Those values are going to be used to compare with my calculated total investment costs for each foundation.

Most of the data comes from the online database "4coffshore.com", which I mentioned already in chapter "Collect data".

The total investment costs include the investment costs for foundation, turbine and electrical infrastructure. A separation is done between Monopile, Gravity base, Tripod and Floating foundations. The data is collected with details on water depth, distance to shore, turbine capacity, data collecting year, country, source and specific costs (see Tab. 10 - Tab. 13 in the appendix).

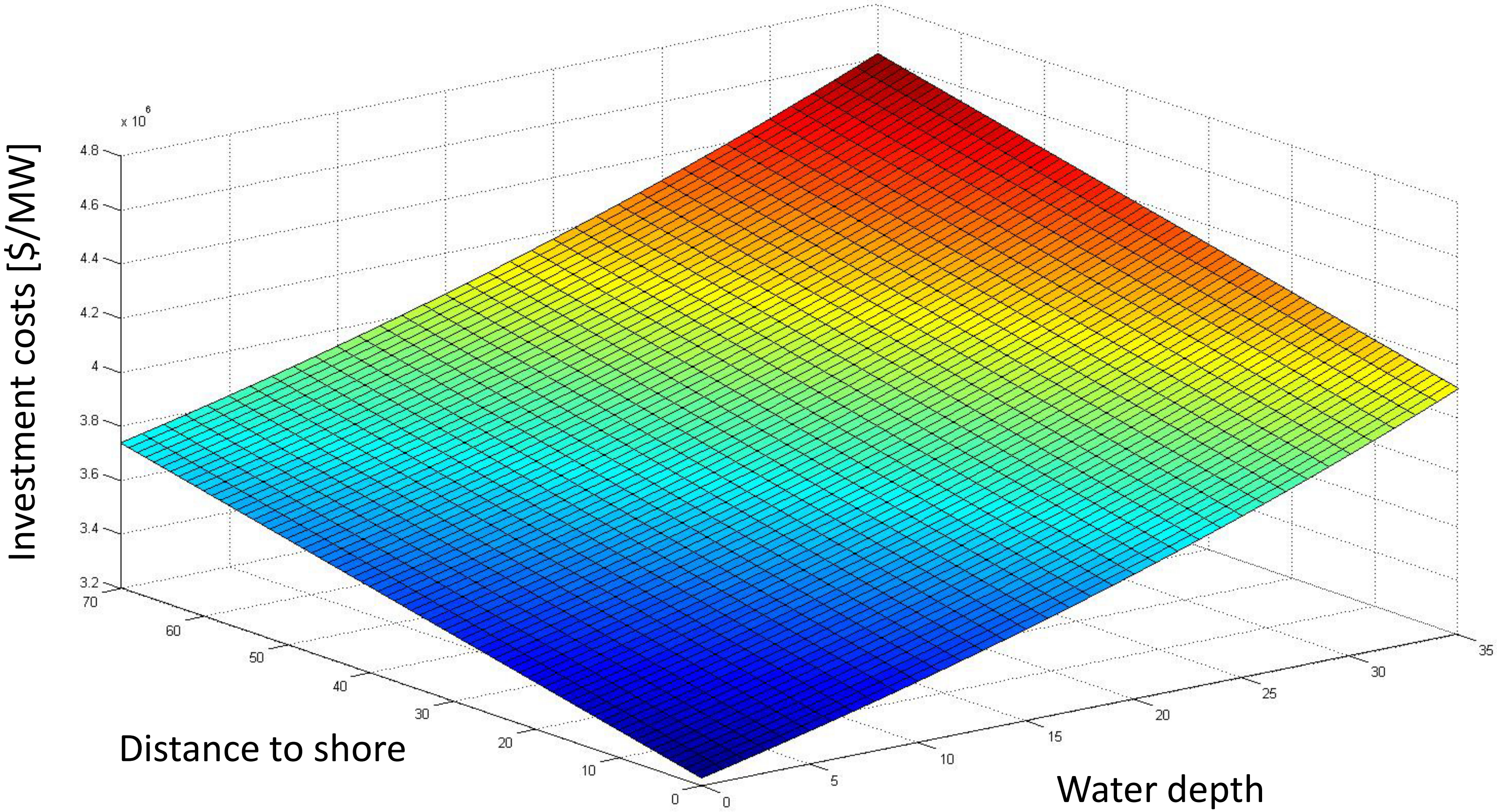


Figure 2: Investment costs [$/MW] of Monopile foundations according to water depth and distance to shore based on own research

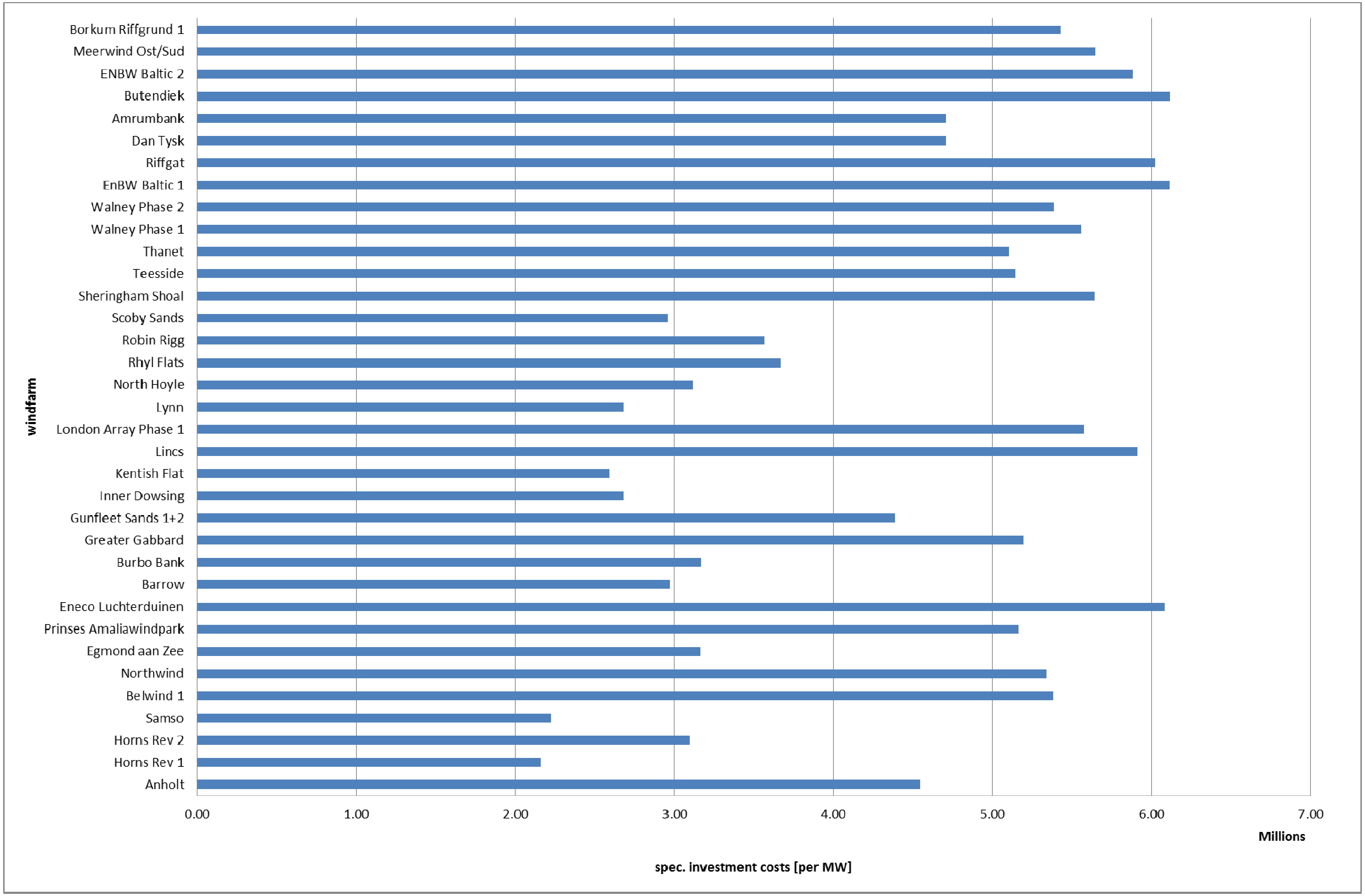


Figure 3: total investment costs [per MW] for Monopile foundations based on past projects

Most of the existing offshore wind farms are built on Monopile foundations in Europe. I could collect investment cost data from 35 “Monopile” wind farms in Denmark, Belgium, Netherlands, Great Britain and Germany. They were all commissioned between 2003 and 2014. Their capacity varies between 2 – 4 MW. The minimal water depth is 5 m, the maximal water depth is 30 m. The distance to shore is in a range from 2.2 – 70 Km. In Tab. 10 you can see the total investment costs [per MW] for Monopile foundations based on data from past projects.

For Gravity base foundations the second most data is provided. Between 2001 and 2013 seven wind farms with Monopile foundations were built in Denmark, Belgium and Sweden. Gravity base foundations are normally used in swallow water. The Belgium wind farm Thornton Bank 1 is built in 25 m deep water. The distance to shore depends from 0.4 – 28 Km.

The Experience with floating foundations is very low and most of the existing ones are still in the development phase and not able to produce electricity economically. There is one floating foundation with a 2 MW wind turbine in Japan, which might be producing electricity economically. It was commissioned 20 Km off the coast of Fukushima in 2013. The water depth is around 100 m. This project has extremely high investment costs of 130 Mill $/MW and is more a showcase after the Fukushima disaster 2011 than a profitable wind farm.

The use of Tripod foundations is popular in Germany. Germany’s first wind farm “Alpha Ventus” is partly built on Tripod foundations in 35 m water depth, 56 Km off the coast. It was commissioned in 2010 with a turbine capacity of 5 MW each. Two other wind farms “Global Tech 1” and “Trianel Windpark Borkum 1” are built in 30 m respectively 40 m water depth.

## Create diagrams based on total investment costs from past projects

The collected data from past projects is going to be plotted in Excel and Matlab as well. The results of the Excel plots are presented in Fig. 9 and Fig. 10.

Fig. 9 shows the specific investment costs [$/MW] according to water depth. The data point for the floating foundation is not including in this diagram. Data points which have the same shape and color belong to the same kind of foundation. Trendlines for each foundation type try to pull those points together. But as you can see on the $R^2$ values of each trendline, there is no correlation between those data points.

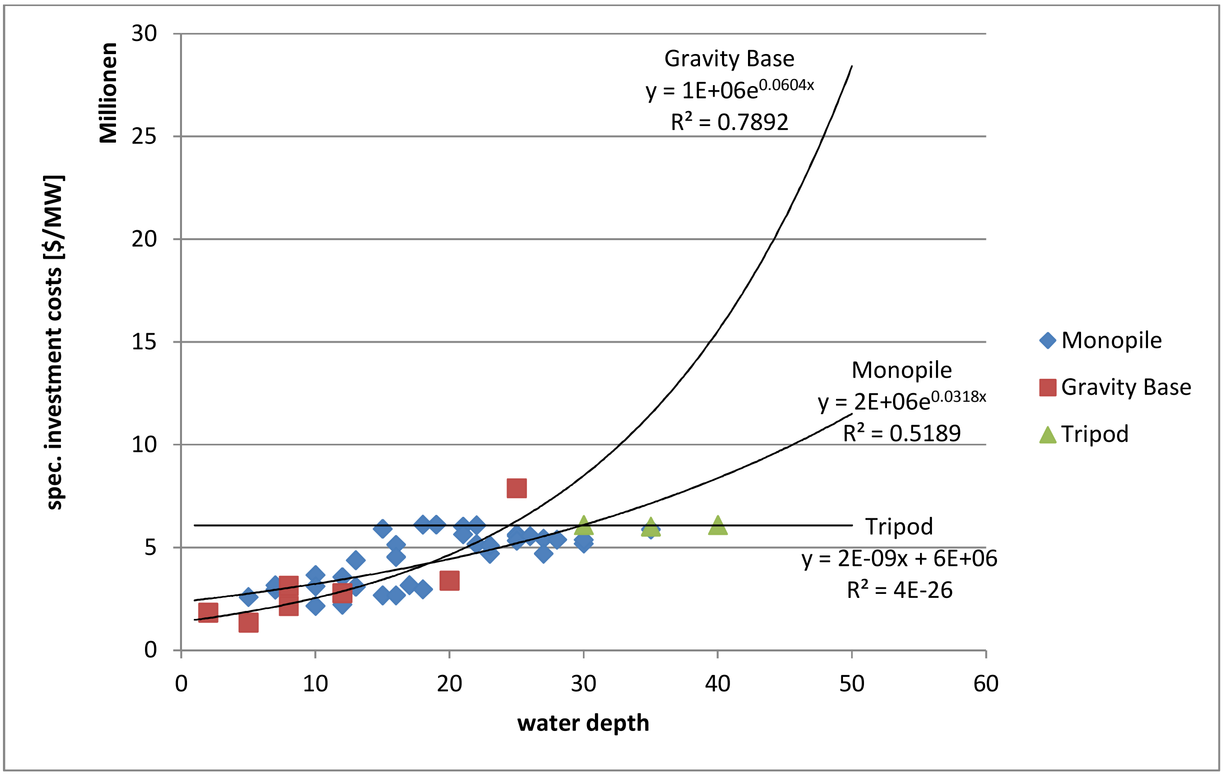


**Fig. 9: spec. investment costs [$/MW] of WT with separation in foundation types according to water depth**

As you could see in Fig. 9 the cheapest solution in application of different types of foundation according to water depth would be the following:

0-18 m: gravity base

18-30 m: Monopile

30-50 m: Tripod

50-150 m: Floating

Fig. 10 shows the specific investment costs [$/MW] according to distance to shore.

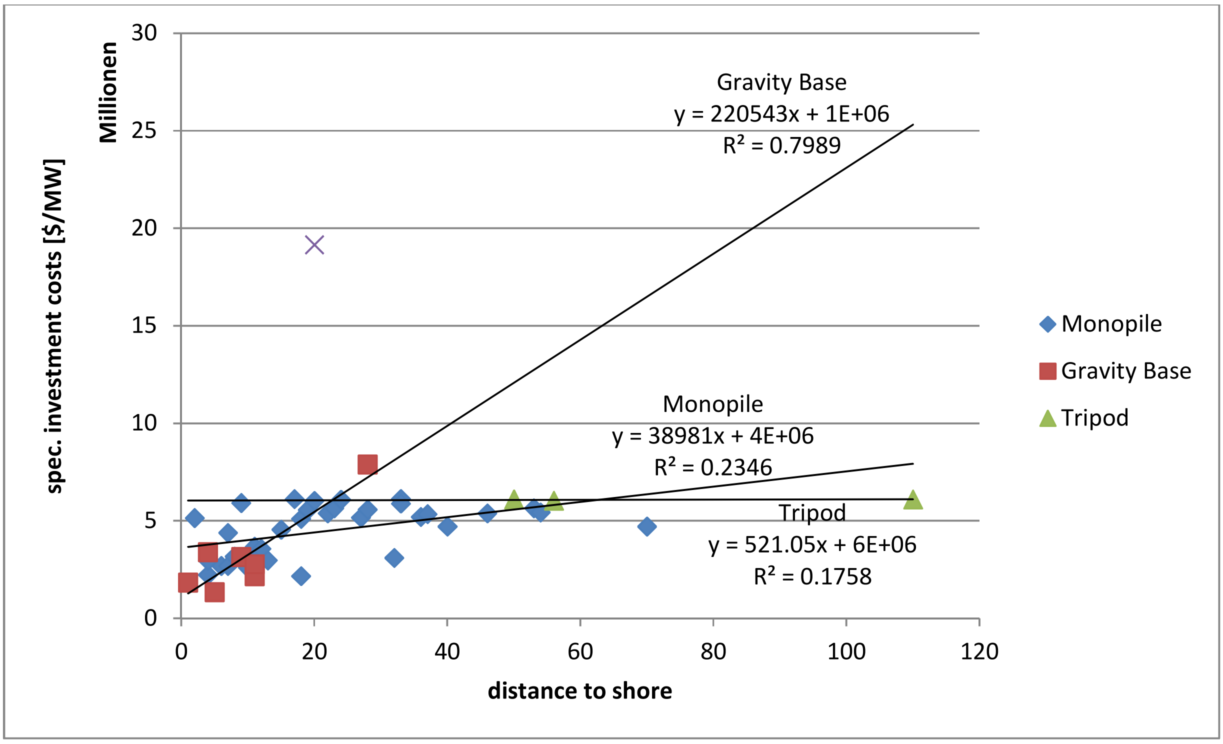


**Fig. 10: spec. investment costs [$/MW] of WT with separation in foundation types according to distance to shore**

As you could see in Fig. 10 the cheapest solution in application of different types of foundation according to distance to shore would be the following:

0-17 Km: gravity base

17-62 Km: Monopile

62-110 Km: Tripod

The Matlab plots for Monopile- and Gravity base foundations are presented in Fig. 11 and Fig. 12.

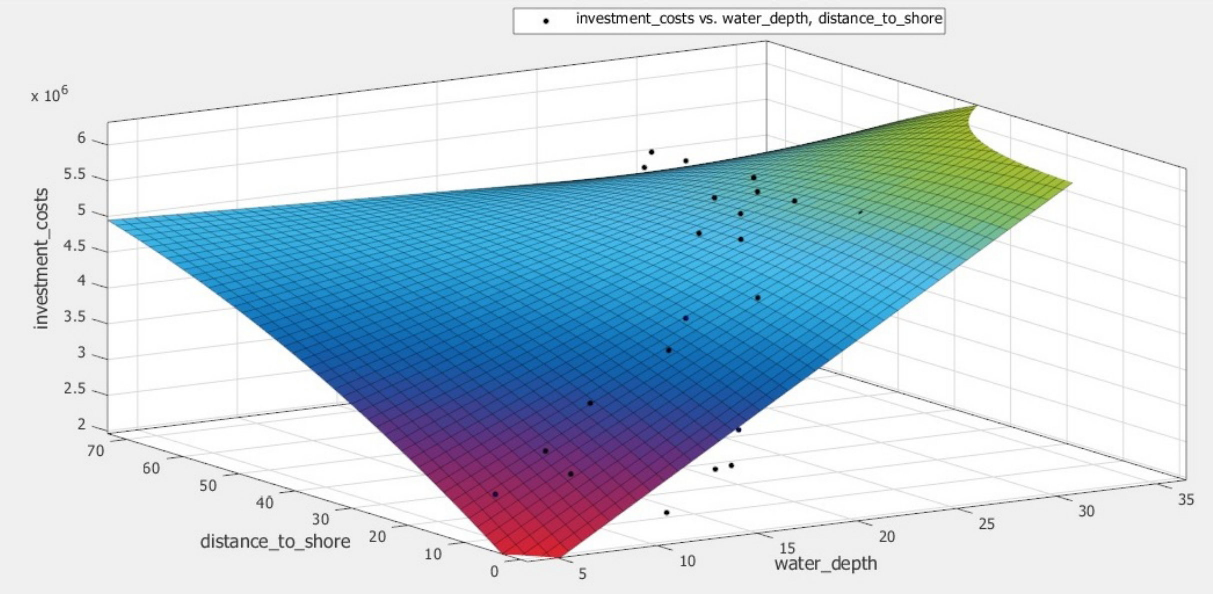


Fig. 11: Matlab plot of investment costs [$/MW] of Monopile foundations according to water depth and distance to shore based on actual data from past projects

The plot is only valid in a certain area. Especially at the border area, this plot does not display the actual investment costs.

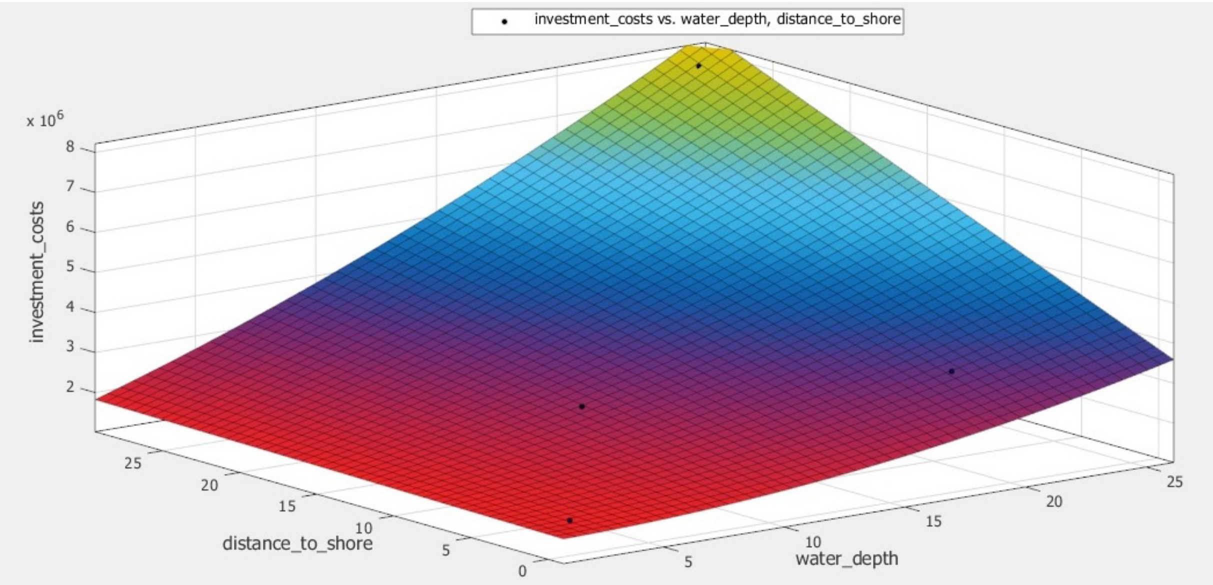


Fig. 12: Matlab plot of investment costs [$/MW] of Gravity base foundations according to water depth and distance to shore based on actual data from past projects

As an analysis result of the data from past projects you could say, that it is nearly impossible to determine an equation dependent on water depth and distance to shore for every foundation type based on the data from past projects, because there is no correlation between the data points.

## Comparison

Nevertheless the collected data is useful to compare certain investment costs at a certain water depth and distance to shore with the calculated ones. The results are shown exemplary for Monopile foundations in Figure 4 and for Gravity base foundations in Figure 5. Blue bars represent the actual investment costs and red bars represent the predicted investment costs based on my equation for Monopile. The offshore wind farms (OWF) are sorted by their commissioning date. You can see that the more recent the OWF is the higher the investment costs are. The actual investment cost is higher than the predicted investment cost, which is based on my equation.

Around 60 % of the investment costs are under calculated compared to actual investment costs. 40 % of the investment costs are over calculated. So all in all, I would say that my calculated equation for total investment costs of a WT using Monopile foundation gives a good general overview about which costs you have to expect.

In Figure 5 you can see the same analysis for Gravity base foundations. The ratio of under- and over calculated investment costs is 14 % to 71 %. Especially for older commissioning dates (10 years ago) the investment costs based on my equation for Gravity base are over calculated. One calculated value fits exact the actual investment cost. It is the wind farm Karehamn in Sweden, built in 2013.

Moreover I guess my equation fits for water depths around 20 m. For shallow water conditions it is overcalculated as well. One exception is the OWF Thornton Bank 1 in Belgium, built in 2009. It is a big OWF with a total capacity of 300 MW. It was Belgiums first OWF and showcase at the same time. I assume that the named reasons could explain the high investment costs of nearly 8 Mill$/MW.

## Calculation of LCOE

The calculation of the levelized cost of energy (LCOE) is very useful to make costs of generation from different energy sources comparable to each other. LCOE calculations assist policy makers, researchers and others to guide discussions and decision making. The LCOE is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital.

Based on DOE's report "A National Offshore Wind Strategy: Creating an Offshore Wind Energy Industry in the United States", 2011 and NREL's technical report "2011 Cost of Wind Energy Review" the LCOE is defined as:

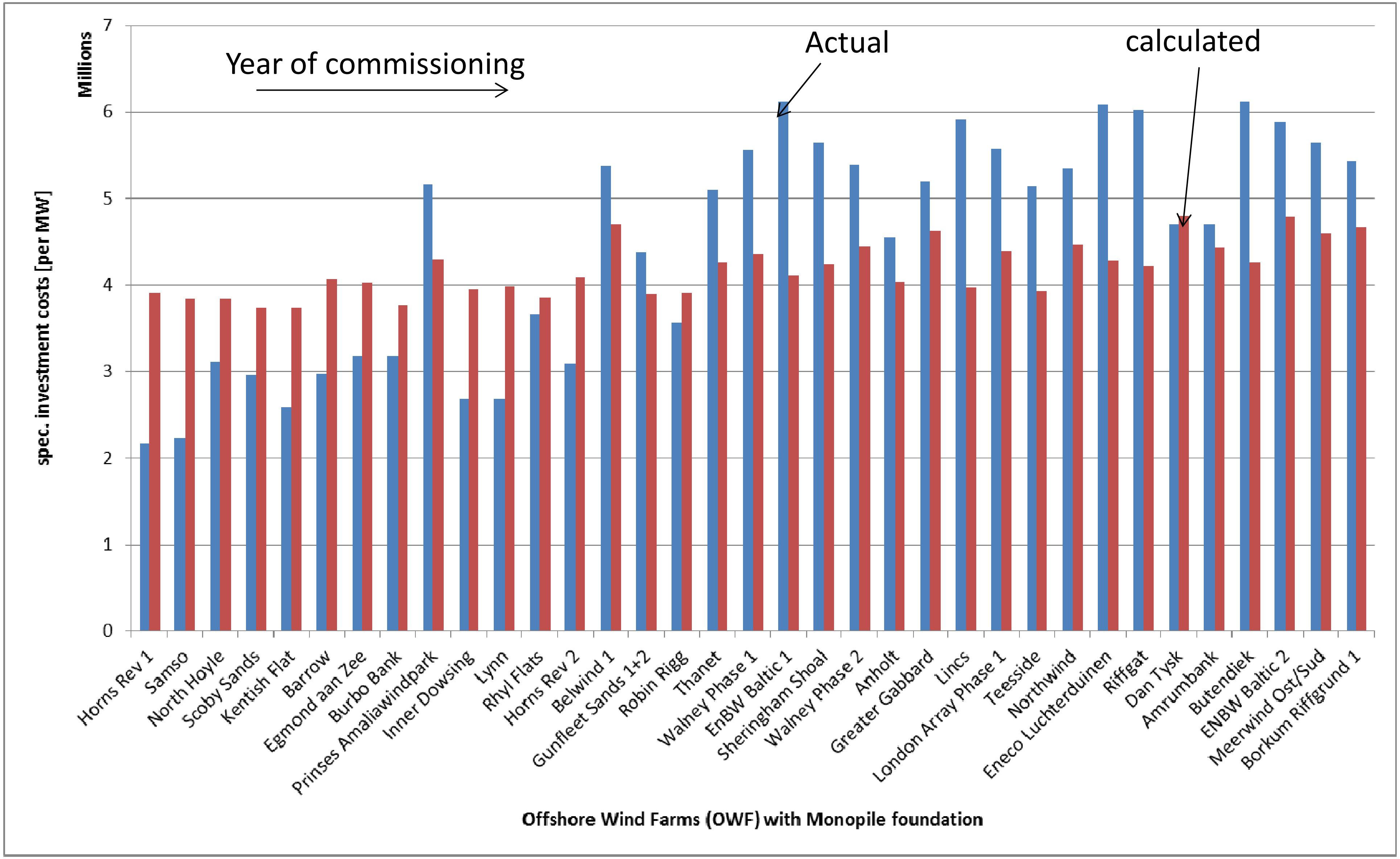


Figure 4: calculated investment costs [per MW] for Monopile foundations in comparison with actual investment costs for different OWF sorted by year

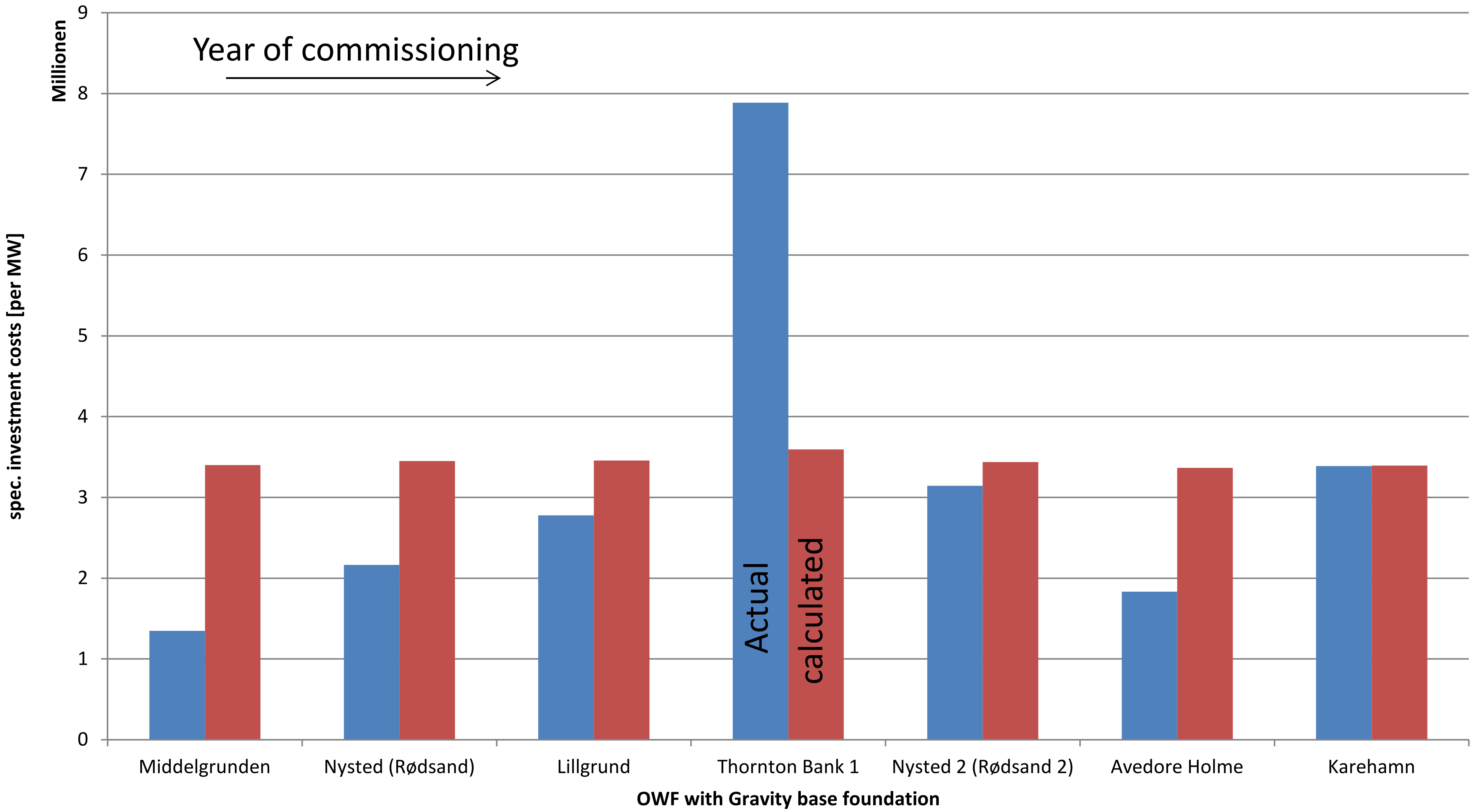


Figure 5: calculated investment costs [per MW] for Gravity base foundations in comparison with actual investment costs for different OWF sorted by year

$$LCOE = \frac{(DRF \times ICC) + O\&M + LRC + Fees}{AEP} \quad [\$/MWh]$$

With:

DRF = discount rate factor
ICC = installed capital costs
O&M = operations & maintenance costs
LRC = levelized replacement costs
AEP = annual energy production
Fees = annual insurance, warrantees, etc.

$$DRF = \frac{d}{1 - 1/(1+d)^N} \times \frac{(1 - T \times PVDEP)}{1 - T}$$

d = discount rate
N = analysis period
T = marginal income tax rate
PVDEP = present value of depreciation

The installed capital costs (ICC) also include additional “soft costs”. Soft costs are insurance, surety bond (decommissioning) and contingency. For a 3.6 MW offshore WT it is around 16 % of the whole ICC cost (~730 $/KW). The choice of the discount rate factor has a high influence on the LCOE. In the following O&M + LRC + Fees are summarized to AOE (Annual Operating Expenditures).

## Comparison of calculations

The following chapter compares LCOE calculations of DOE, NREL, Amy Chiang and me. The results can be seen in Tab. 7.

Tab. 7: Comparison of values to calculate LCOE [$/Kwh]

| | ICC [$/KW] | DRF [%] | turbine capacity [MW] | AEP [MWh/MW] | AOE [$/KW] | capacity factor [%] | year | **LCOE [$/Kwh]** |
|---|---|---|---|---|---|---|---|---|
| DOE | 4,259 | 20 | 3.6 | 3,410 | 69 | 39 | 2010 | **0.27** |
| NREL | 5,600 | 11,8 | 3.6 | 3,406 | 107 | 39 | 2011 | **0.23** |
| Amy Chiang | 4,897 | 20 | 3 | 3,419 | 107 | 39 | 2014 | **0.32** |
| Amy Chiang | 4,897 | 11.8 | 3 | 3,419 | 107 | 39 | 2014 | **0.20** |
| Eric | 5,262 | 20 | 3 | 3,419 | 107 | 39 | 2014 | **0.34** |
| Eric | 5,262 | 11.8 | 3 | 3,419 | 107 | 39 | 2014 | **0.21** |

The main difference between the values is that DOE calculates their LCOE with a DRF of 20 %, while NREL calculates it with 11.8%. This affects the LCOE about 4 Cents/Kwh. Because of that, two calculations for Amy's and my values were done. One with a DRF factor of 20 % and one with a DRF factor of 11.8 %.

Amy's and my total investment costs include production, transport and installation of foundation, turbine and electrical infrastructure. Not include are development costs, project management costs, "soft costs" and construction financing costs. NREL calculates those costs to 1068 $/KW in total. I am going to add those costs to Amy's and my total investment costs to get the ICC costs. The AOE, which includes O&M + LRC + Fees, is assumed to 107 $/KW based on the NREL's report.

The calculation shows that Amy and I could reach similar values for LCOE compared to DOE's und NREL's calculations. Main factors are definitely the made assumptions for AOE and "soft costs" as well as the used DRF.

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Wagner. Windenergienutzung und Lebenszyklusanalyse, 2013

Weinzettel. Life cycle assessment of a floating offshore wind turbine, 2008

# Appendix

Tab. 8: Used data sources for my research and their year of publication

| source | kind of source | year |
|---|---|---|
| M. Dicorato. Guidelines for assessment of investment cost for offshore wind generation | article | 2012 |
| Lundberg. Performance comparison of wind park configuration. | Technical report | 2003 |
| Elkinton. Offshore windfarm layout optimization project | project report | 2005 |
| Nielsen. Offshore wind energy projects feasibility study guidelines | project report | 2003 |
| Danish Wind Energy Association | website windpower.org | 2010 |
| DTI. Study of the costs of offshore wind generation | working paper | 2007 |
| Gooch: An Energy and Cost Based GIS Approach to Offshore Wind Farm Site Mapping; Bellone et al. | project report | 2007 |
| Douglas-Westwood. Offshore Wind Assessment For Norway | report | 2010 |
| Myhr. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective | article | 2014 |
| Optimal integrated combination of foundation, Den Helder, Ballast Nedam GBS foundation producer | speech slides | 2009 |
| MonobaseWind | speech slides | 2012 |
| Borgen. Floating Wind Power in Deep Water - Competitive with Shallow-water Wind Farms? | report | 2010 |
| Nikolaos. Deep water offshore wind technologies | Master thesis | 2004 |
| EWEA | report | 2004 |
| IRENA: Renewable Energy Technologies | report | 2012 |
| Ernst & Young | prediction | 2009 |

| | | |
|---|---|---|
| | report | |
| Risoe DTU, Technical University of Denmark | talk slides ENERTECH 2009 Athens | 2009 |
| Roland Berger. Offshore Wind Study | study report | 2013 |
| NREL. Technical report. Cost of wind energy review | Technical report | 2012 |
| NREL. Electrical Collection and Transmission Systems for Offshore Wind Power | Technical report | 2007 |
| 4coffshore.com | website | access Dec. 2014 |
| Seawind prediction | case study report | 2001 |

**Tab. 9: inflation of USD and exchange values of different foreign currencies**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| inflation USD | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| year | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| inflation | $1.29 | 1.26 | 1.22 | 1.18 | 1.15 | 1.1 | 1.11 | 1.09 | 1.06 | 1.04 | 1.02 | 1 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| exchange from different currencies into USD | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| year | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| average value NOK -> USD | 0.141177 | 0.148662 | 0.155489 | 0.156108 | 0.171112 | 0.179786 | 0.15977 | 0.165661 | 0.178596 | 0.171924 | 0.170267 | 0.16025 |
| average value SEK -> USD | 0.124372 | 0.136263 | 0.134385 | 0.135785 | 0.148143 | 0.153504 | 0.131543 | 0.139097 | 0.154216 | 0.147738 | 0.153515 | 0.146952 |
| average value GBP -> USD | 1.635499 | 1.832895 | 1.820271 | 1.842866 | 2.00156 | 1.855443 | 1.565394 | 1.545893 | 1.604123 | 1.584877 | 1.564768 | 1.651515 |
| average value EUR -> USD | 1.134134 | 1.243633 | 1.244729 | 1.256316 | 1.370503 | 1.471366 | 1.393096 | 1.326984 | 1.392705 | 1.285697 | 1.328247 | 1.355397 |

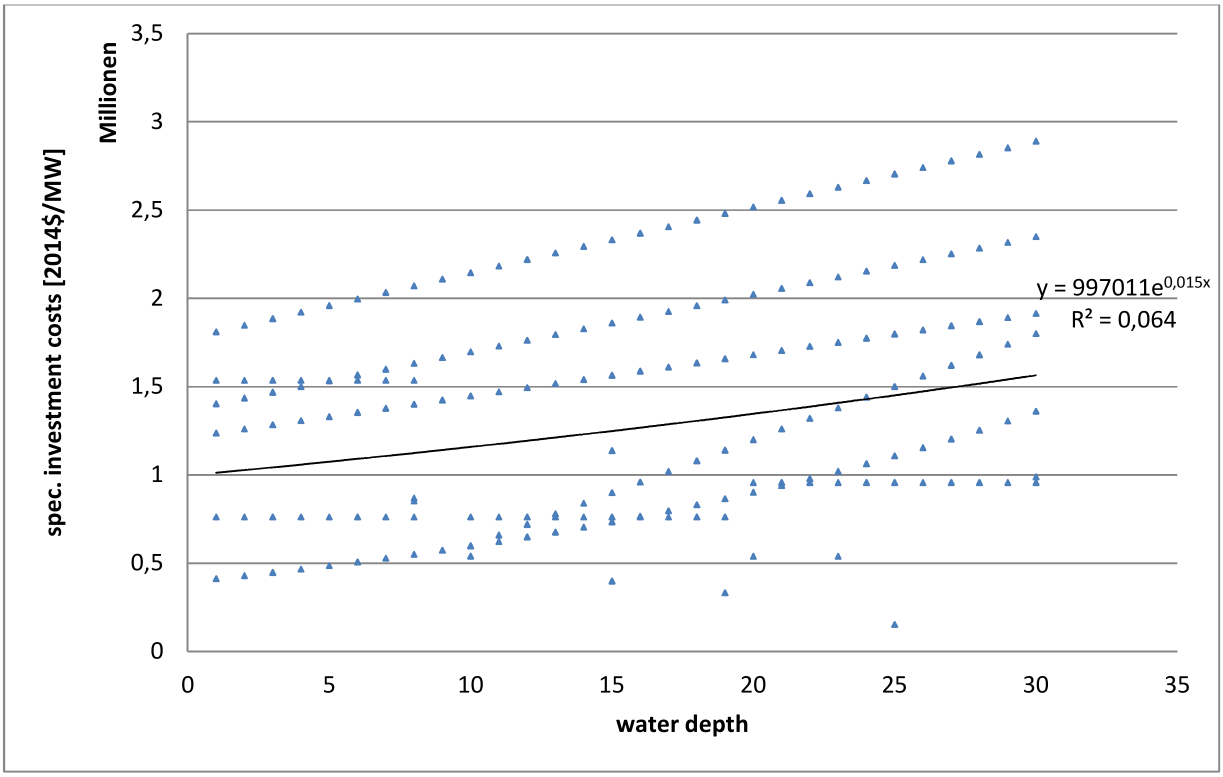


**Fig. 13: Trendline for Monopile investment costs according to water depth with predicted data points from Seawind case study**

### Tab. 10: Database with actual data from past projects for Monopile foundations

| **Monopile** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| project | water depth | distance to shore [Km] | turbine capacity [MW] | data collecting year | country | source | all spec. investment costs Monopile [per MW] | value 2014 $ all spec. investment costs Monopile [per MW] |
| | | | | | | | | |
| include foundation, turbine and electrical components | | | | | | | | |
| Anholt | 16 | 15 | 3.6 | 2013 | Denmark | 4coffshore.com | 25,025,000 | 4545606.57 |
| Horns Rev 1 | 10 | 18 | 2 | 2002 | Denmark | 4coffshore.com | 1,738,000 | 2162172.39 |
| Horns Rev 2 | 13 | 32 | 2.3 | 2010 | Denmark | 4coffshore.com | 2,140,000 | 3095322.30 |
| Samso | 12 | 4.2 | 2.3 | 2003 | Denmark | 4coffshore.com | 1,521,739 | 2226354.16 |
| Belwind 1 | 30 | 46 | 3 | 2010 | Belgium | 4coffshore.com | 3,721,212 | 5382406.76 |
| Northwind | 25 | 37 | 3 | 2014 | Belgium | 4coffshore.com | 3,939,815 | 5340014.31 |
| Egmond aan Zee | 17 | 10 | 3 | 2007 | Netherlands | 4coffshore.com | 2,010,000 | 3167917.11 |
| Prinses Amaliawindpark | 22 | 26.5 | 2 | 2008 | Netherlands | 4coffshore.com | 3,191,666 | 5165719.72 |
| Eneco Luchterduinen | 22 | 24.2 | 3 | 2014 | Netherlands | 4coffshore.com | 4,488,372 | 6083526.94 |
| Barrow | 18 | 12.7 | 3 | 2006 | Great Britain | 4coffshore.com | 1,366,667 | 2971929.29 |
| Burbo Bank | 7 | 8 | 3.6 | 2007 | Great Britain | 4coffshore.com | 2,011,000 | 3169493.18 |
| Greater Gabbard | 30 | 36 | 3.6 | 2013 | Great Britain | 4coffshore.com | 5,196,429 | 5196429.00 |
| Gunfleet Sands 1+2 | 13 | 7.4 | 3.6 | 2010 | Great Britain | 4coffshore.com | 22,569,444 | 4383696.06 |
| Inner Dowsing | 15 | 6.2 | 3.6 | 2009 | Great Britain | 4coffshore.com | 1,543,201 | 2681446.52 |
| Kentish Flat | 5 | 9.8 | 3 | 2005 | Great Britain | 4coffshore.com | 1,166,667 | 2590853.13 |
| Lincs | 15 | 9.1 | 3.6 | 2013 | Great Britain | 4coffshore.com | 3,703,703 | 5911344.65 |
| London Array Phase 1 | 25 | 27.6 | 3.6 | 2013 | Great Britain | 4coffshore.com | 3,492,063 | 5573553.81 |
| Lynn | 16 | 6.9 | 3.6 | 2009 | Great Britain | 4coffshore.com | 1,543,210 | 2681462.16 |
| North Hoyle | 10 | 9.2 | 2 | 2004 | Great Britain | 4coffshore.com | 1,350,000 | 3117754.40 |
| Rhyl Flats | 10 | 10.7 | 3.6 | 2009 | Great Britain | 4coffshore.com | 2,111,111 | 3668239.75 |
| Robin Rigg | 12 | 11.5 | 3 | 2010 | Great Britain | 4coffshore.com | 2,116,666 | 3566631.68 |
| Scoby Sands | 7 | 3.5 | 2 | 2004 | Great Britain | 4coffshore.com | 1,280,000 | 2956093.06 |
| Sheringham Shoal | 21 | 23 | 3.6 | 2012 | Great Britain | 4coffshore.com | 31,565,656 | 5643969.60 |
| Teesside | 16 | 2.2 | 2.3 | 2013 | Great Britain | 4coffshore.com | 3,220,612 | 5140300.81 |
| Thanet | 23 | 17.7 | 3 | 2011 | Great Britain | 4coffshore.com | 3,000,000 | 5101111.14 |
| Walney Phase 1 | 26 | 19.3 | 3.6 | 2011 | Great Britain | 4coffshore.com | 3,267,974 | 5556766.19 |
| Walney Phase 2 | 28 | 22 | 3.6 | 2012 | Great Britain | 4coffshore.com | 3,267,974 | 5386510.30 |
| EnBW Baltic 1 | 18 | 17 | 2.3 | 2011 | Germany | 4coffshore.com | 4,140,786 | 6112906.97 |
| Riffgat | 21 | 20 | 3.6 | 2014 | Germany | 4coffshore.com | 4,444,444 | 6023987.05 |
| Dan Tysk | 27 | 70 | 3.6 | 2014 | Germany | 4coffshore.com | 3,472,222 | 4706240.05 |
| Amrumbank | 23 | 40 | 3.6 | 2014 | Germany | 4coffshore.com | 3,472,222 | 4706240.05 |
| Butendiek | 19 | 33 | 3.6 | 2014 | Germany | 4coffshore.com | 4,513,888 | 6118111.26 |
| ENBW Baltic 2 | 35 | 33 | 3.6 | 2014 | Germany | 4coffshore.com | 4,340,278 | 5882800.74 |
| Meerwind Ost/Sud | 25 | 53 | 3.6 | 2014 | Germany | 4coffshore.com | 4,166,667 | 5647488.88 |
| Borkum Riffgrund 1 | 27 | 54 | 4 | 2014 | Germany | 4coffshore.com | 4,006,410 | 5430276.99 |

### Tab. 11: Database with actual data from past projects for Gravity base foundations

| **Gravity based** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| project | water depth | distance to shore [Km] | turbine capacity [MW] | data collecting year | country | source | all spec. investment costs gravity based [per MW] | value 2014 $ all spec. investment costs gravity based [per MW] |
| | | | | | | | | |
| include foundation, turbine and electrical components | | | | | | | | |
| Avedore Holme | 2 | 0.4 | 3.6 | 2011 | Denmark | 4coffshore.com | 9,259,000 | 1834396.41 |
| Middelgrunden | 5 | 4.7 | 2 | 2001 | Denmark | 4coffshore.com | 1,122,250 | 1347371.62 |
| Nysted (Rødsand) | 8 | 10.8 | 2.3 | 2003 | Denmark | 4coffshore.com | 1,479,469 | 2164511.76 |
| Nysted 2 (Rødsand 2) | 8 | 9 | 2.3 | 2010 | Denmark | 4coffshore.com | 2,173,900 | 3144355.67 |
| Thornton Bank 1 | 25 | 28 | 5 | 2009 | Belgium | 4coffshore.com | 5,100,000 | 7886315.98 |
| Lillgrund | 12 | 11.3 | 2.3 | 2007 | Sweden | 4coffshore.com | 16,304,347 SEK | 2777681.11 |
| Karehamn | 20 | 3.8 | 3 | 2013 | Sweden | 4coffshore.com | 2,500,000 | 3387028.58 |
| | | | | | | | | |

**Tab. 12: Database with actual data from past projects for Tripod foundations**

| Tripod | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| project | water depth | distance to shore [Km] | turbine capacity [MW] | data collecting year | country | source | all spec. investment costs tripod [per MW] | value 2014 $ all spec. investment costs tripod [per MW] |
| include foundation, turbine and electrical components | | | | | | | | |
| Alpha Ventus | 35 | 56 | 5 | 2010 | Germany | 4coffshore.com | 4,167,667 | 6028164.76 |
| Global Tech 1 | 40 | 110 | 5 | 2014 | Germany | 4coffshore.com | 4,500,000 | 6099287.50 |
| Trianel Windpark Borkum 1 | 30 | 50 | 5 | 2014 | Germany | 4coffshore.com | 4,500,000 | 6099287.50 |

**Tab. 13: Database with actual data from past projects for Floating foundations**

| Floating | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| project | water depth | distance to shore [Km] | turbine capacity [MW] | data collecting year | country | source | all spec. investment costs floating [per MW] | value 2014 $ all spec. investment costs floating [per MW] |
| include foundation, turbine and electrical components | | | | | | | | |
| Fukushima MIRAI | 100 | 20 | 2 | 2014 | Japan | 4coffshore.com | 130,000,000 | 130,000,000 |

The Matlab plots are created with a curve fitting tool. You can start it in Matlab by typing “cftool” in the Command window. The implementation code for adding the data points to a mesh grid is exemplary shown for the Monopile foundation:

```
implementation_monopile

x=[0:35]; y=[0:70];

[X,Y]=meshgrid(x,y);

z1=2242483.33 + 7236*Y + 986059*exp(0.0182*X);

surface(X,Y,z1) ;

xlabel('water depth');

ylabel('distance to shore');

zlabel('total investment costs');

title('total investment costs of WT with Monopile foundation according to water depth and distance to shore');

mesh(X,Y,z1)

surface (X,Y,z1)
```

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