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Trends in offshore wind economics – the past and the future

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Abstract— Expectations to the development of offshore wind are high, especially in Europe. Offshore wind is expected to contribute significantly to the reaching on renewable energy targets, in 2020 and beyond. However, offshore wind power plants are expensive. They currently still cost approximately twice as much as onshore wind. Moreover, upfront investment costs make up to 75% of the total lifetime cost, which makes financing extremely difficult. We investigate the development of offshore wind based on a unique collection of economic data comprising all major offshore wind power plants in Europe. We use our data set to investigate trends in investment cost, operation and maintenance cost, financing and profitability, and identify key economic drivers for offshore wind energy. More specifically, we analyse economic consequences in areas such as project sizes, turbine capacity, distance to shore and water depth, as well as the interrelations of the economic drivers in the areas. We then proceed to analysing industry expectations of cost reductions for offshore wind. This includes both previous cost reduction expectations and in how far they could be realised, as well as current cost reductions. We set them in perspective and identify the most important drivers for cost reductions in European offshore wind in the short and long term.

Keywords-offshore wind; technology cost; renewable energy

I. INTRODUCTION

Offshore wind is rapidly developing. By the end of 2014, the offshore wind industry reached a total capacity of 8,759 MW worldwide, of which 91%, or 8,045 MW, was in Europe [1]. Taking projects into consideration which are currently under construction (mid 2015), this number increases to more than 12 GW in Europe alone. The development is dominated by only a handful of countries: In 2014, the UK has installed almost half of the total new capacity (47%), followed by Germany (31%) and China (13%). The UK seems to be able to maintain its leading position in the coming years with quite a number of new projects either under construction or in the planning process.

Expectations to the development of offshore wind are high, especially in Europe. The European Wind Energy Association (EWEA) expects a total capacity of between 19.5 and 27.8 GW by 2020 in Europe. This implies a growth rate between 20 and 27% p.a., much in line with the realised growth rates of recent years (33% in 2012, 31% in 2013, and 23% in 2014). This is, however, significantly less than what

the EU member states have reported as expected growth in their National Renewable Energy Action Plans (NREAPs), reaching 43 GW of offshore wind in 2020 in Europe [2]. For this, the growth rates would need to be significantly accelerated.

In this paper, we investigate the economics behind the past offshore development in Europe and analyse industry expectations of future cost reduction potentials. This way, we aim to contributing to the discussion about what the role of offshore wind should be in the future European energy system.

The remainder of the paper is structured as follows. In section II, we shortly set our analysis into perspective referring to the related literature and explaining our methods in the data analysis. In sections III and IV we present the major cost components and their levels in European offshore wind power plants. In section V we then analyse four major economic drivers in the past, before we proceed to the future outlook in section VI. We conclude with section VII.

II. SCIENTIFIC CONTEXT AND METHODS

A. Relevant literature

Much scientific literature dedicated to offshore wind deals with the technology in general or in detail, or with managerial aspects of projects. Some broader technological publications, such as [3], who comprehensively describe all basics of offshore wind, also deal with some of the cost elements. Also [4] provides an overview of the state of offshore wind including current cost estimates.

Scientific literature dedicated solely to the economics of offshore wind is rare. An overview of the main issues associated with the economics of offshore wind is given in [2]. This 2011 paper spans broadly from cost, over support schemes, to power market and integration issues. Such broad perspective makes it, however, difficult to go into detail with e.g. specific cost elements. This has been partly achieved in [5], a report from 2009. Here, the economics of wind power have been comprehensively described (on basis of the at that time available data), and the report still serves as a major source for many analyses. In 2009, the market was, however, still rather immature and analyses could not draw from very many actually realised offshore wind power plants. This has changed now.

With the analysis presented here, we strive to close the gap in scientific literature, providing a more detailed analysis of cost elements and their economic drivers and analysing key figures from a comprehensive data set comprising more offshore wind power plants than in any of the previous publications.

B. Data set

For the purpose of analysing the economics of offshore wind, and more specifically their cost development, we have gathered a data set comprising information about all commercial offshore wind power plants in Europe, from the first plant in Denmark, Middelgrunden, with 20 turbines and a total capacity of 40 MW, which was built in 2000, to the latest projects of 400-600 MW in Germany and the Netherlands that will be commissioned until 2017.

The comprehensive data set combines public information from [6], [7], [3], [8] and several project websites, with internal and more informal information gathered throughout years of research at Risø DTU.

The data set has 60 commercial offshore wind projects (larger than 10 MW), with 7 offshore wind power plants in Denmark, 15 in Germany, 25 in the UK, and 13 elsewhere (in the Netherlands, Belgium, Sweden, Finland and Ireland). In total, it comprises 12.2 GW of capacity and an investment volume of 42.8 billion Euro. The information collected includes location, commissioning date, turbine size, turbine manufacturer and type, distance to shore, water depth, investment cost, annual production, as well as operations and maintenance cost wherever available.

We base our analysis on this data set, so when no additional source is explicitly mentioned, we derive the data from the data set with reference to the sources described above.

III. INVESTMENT COSTS

Offshore wind power plants are highly capital-intensive. Upfront investment costs make up approximately 75% of the total lifetime cost, which is extremely high in comparison to conventional power plants (where investment costs typically constitute around 40% of the lifetime cost). Offshore wind is also considerably more expensive than onshore wind: Investment costs per MW are approximately 50% higher, which is mostly due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations, and grid connection are significantly higher than for onshore wind. Typically, offshore turbines are 20% more expensive, and towers and foundations cost more than 2.5 times the price of an onshore project of similar size.

A. Development of investment costs

Overall, the specific investment cost (per MW cost) of offshore wind power has not decreased as previously seen in the development of onshore wind. On the contrary, specific investment costs have increased substantially, from on average 2.1 m€/MW in the first decade of the century, to 3.7 m€/MW for wind power plants commissioned from 2010 onwards.

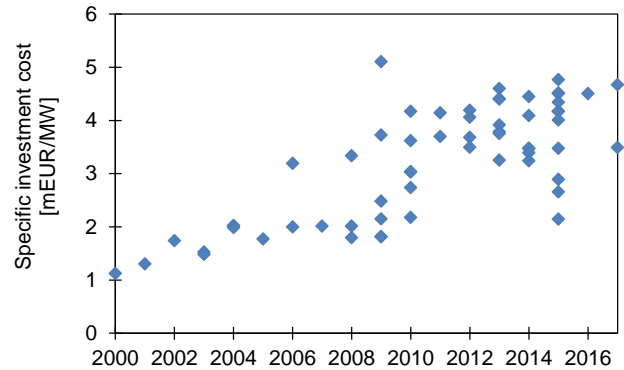


Figure 1. Development of investment costs of European offshore wind power plants between 2000 and 2017 (year of commissioning)

Fig. 1 shows the development of this general increase of specific investment costs. This is despite the significant increase in project sizes and consequently potential economies of scale. The main reasons for this increase are to be found in increasing distances to shore and water depths, as analysed below. Furthermore, towards the end of the last decade, supply bottlenecks and increasing component prices occurred.

B. Investment cost components

The investment cost of an offshore wind power plant is typically split into a limited number of cost components, including the turbine itself, foundation, cabling etc. For our cost comparison, we use the categorisation as shown in Table 1.

TABLE I. INVESTMENT COST COMPONENTS

Cost components	Examples for detailed cost items
Development and project management	Design, management, consenting, consultancy fees,
Turbines	Tower, rotor blades, rotor hub, rotor bearings, main shaft, main frame, gear box, generator, yaw system, pitch system, power converter, transformer, brake system, nacelle housing, cables
Foundations	Foundations, transition piece
Electrical installations (offshore) (including Balance of plant)	Collection system, integration system, offshore substation, transmission system, reactive power compensation system, electrical devices, export cable (main cable to coast)
Grid connection (onshore)	Dedicated cables onshore, isolators, switchgear under control of onshore network operator
Installation (of turbines, foundations, cables and electrical equipment)	Transportation cost, vessel chartering costs, labour cost
Financial costs	Financing, bank fees, securities
Miscellaneous	Services, insurance and other overheads

Turbines are the most costly element of an offshore wind project, accounting for between 40% and 60% of the total investment cost. Turbine blades and towers make approximately half the total turbine costs [9]. Installation is typically the largest cost item after the turbines themselves, with roughly a quarter of the total investment cost. Installation costs are, however, often not visible in cost breakdowns, as they often are shown as integrated part of turbine, foundation and cable costs, respectively. The third-largest cost component, foundations, accounts for approximately 20% of the investment costs.

Overall, approximately one third of the total investment cost is labour costs, another third is materials and the last third comprises services, insurance and other overheads [10]. Key commodities in the material cost are fibreglass, steel, iron and copper, which make e.g. 90% of the material cost of a turbine [10]. The split into cost components will of course vary considerably between projects.

Compared to onshore projects, the main differences in the cost structure stem from two elements. Firstly, the offshore foundations are considerably more expensive. The costs depend on the water depth, but also on the chosen foundation type and technology. In an onshore project with conventional foundations, the cost component makes approximately 5-9% of total cost, whereas offshore foundations can make up to 20%. Secondly, substation and transmission cables cause additional costs compared to onshore projects, which can make up to 13-21% of total costs.

IV. OPERATION AND MAINTENANCE COSTS

Next to investment cost, Operation and Maintenance (O&M) costs constitute a sizeable share of the total costs of offshore wind. O&M costs may easily make up between 25% and 30% of the total lifetime costs of a project. If the project is fairly new, the share may only be 20-25%, but this might increase to at least 30-35% by the end of the lifetime. As a result, O&M costs are beginning to attract greater attention, now that the first offshore wind projects reach the later stages of their lifetime. Manufacturers attempt to lower O&M costs significantly by developing new turbine designs that require fewer regular service visits and less turbine downtime, which is especially important for offshore projects. Condition monitoring is being developed as a technology that can be added to existing and new designs.

A. Estimates of Operations and Maintenance costs

In the past, lifetime average O&M cost have been estimated spanning a broad range from 15 €/MWh to 49 €/MWh. Table 2 shows several different O&M estimations from the literature. Here, it has to be noted that existing data on O&M are clouded by a series of required and expensive retrofits on some of the early offshore wind power plants, partly invisible costs covered in the investment cost through warranty periods and politically-driven pricing of early service agreements [4, p. 17].

TABLE II. ESTIMATES OF O&M-COSTS FOR OFFSHORE WIND

Type of estimate and source	Operation and Maintenance Cost [€/MWh] ^a
Operating offshore wind power plants, EU, 2002-2009 [5]	18
Danish technology data catalogue, average expectations for 2015 [8]	19
German projects, 2010 [7]	27
Survey on UK projects, 2010 [10]	22-27
Offshore power plants in Europe [11]	25-49

a. All prices converted to Euros, real 2012

O&M costs depend heavily on the distance to shore, which affects location of service staff and methods of transfer, both connected to significant health and safety considerations [10]. For distances of more than 50 km from the port, sea-based maintenance concepts may become more efficient than land-based maintenance [12].

Thus, O&M costs for offshore wind power plants tend to be highly specific for the considered plant and average cost estimates are very uncertain and should be used with caution.

B. Operation and Maintenance cost components

Offshore O&M costs can be categorised into a limited number of cost components, including:

- Insurance;
- Regular maintenance;
- Repair;
- Spare parts;
- Access to platform and turbines, and
- Administration.

Several of these O&M costs are rather difficult to estimate. Due to weather-related access restrictions and longer distances to offshore sites, labour-related costs tend to be significantly higher and less predictable than for onshore projects. Whereas standard long term contracts for insurance and regular maintenance can be obtained for onshore turbines, this is not necessarily the case for offshore turbines. Finally, costs for repair and related spare parts are always difficult to predict. Although all cost components tend to increase as the turbine gets older, costs for repair and spare parts are particularly influenced by turbine age, starting low and increasing over time.

V. KEY ECONOMIC DRIVERS

In this paper, we focus on the economics of offshore wind as affected by different cost drivers, setting aside the revenue part (such as income from power markets or support schemes). Drivers that are mostly influenced by external developments are not discussed here, such as cost of finance, exchange rates, etc.

Intrinsic cost drivers include project size, project location (water depth and distance to shore), turbine design, lifetime of the components, planning and consent, etc. These drivers can be mostly influenced by offshore wind developers through technological or managerial choices. In the following, we present four major ones of these drivers, by analysing their development for the case of European offshore wind over the last 15 years.

A. Turbine capacity and overall project size

The size of commercial offshore wind power plants in Europe has increased significantly over time. Whereas the average project size was 88 MW in the first decade of the century (with projects between 10 MW and 209 MW), the past years saw a sharp increase of project sizes. This is illustrated in Fig. 2. The average size of offshore wind power plants installed in Europe between 2010 and 2017 (commissioning date) is 277 MW, with projects ranging between 48 MW and 630 MW, the latter being London Array 1 which was at the time of completion the largest offshore wind power plant in the world and the largest wind power plant in Europe.

Equally, the turbine sizes have increased, from an average of 2.6 MW between 2000 and 2009, to an average of 3.8 MW in the newer developments. Overall, turbine capacities range between 2.0 MW and 6.15 MW. The first offshore wind power plants in Denmark and the UK all used either Siemens or Vestas turbines in the 2-3 MW class. Then, there came a long period where the Siemens 3.6 MW turbine was dominantly used. Today, 45% of all turbines installed in European waters have a capacity of 3.6 MW. Larger turbines were first installed in Belgium in the Thornton Bank project and in Germany in the Alpha Ventus and Nordsee Ost projects from 2009 onwards, first with 5 MW and then 6.15 MW turbines (both Repower). Recently, also Areva has entered the market with a 5 MW turbine. The development of turbine size is illustrated in Fig. 3.

The size of a project is of significant economic importance, because some cost components are (largely) independent from size. Thus, we expect that (*other things equal*) the larger the project, the lower the specific investment costs in m€/MW - a typical case of economies of scale.

Applying regression analyses, we attempt to estimate the economics of scale. Using the specific investment cost (m€/MW) as the dependent variable and the capacity, distance from shore, water depth and a dummy¹ as explaining variables, economies of scale is estimated to be around -0.08, implying that 10% increase in capacity of the given wind power plant would decrease cost by 0.8%. However, the capacity-coefficient is barely significant, so this estimate is quite uncertain.

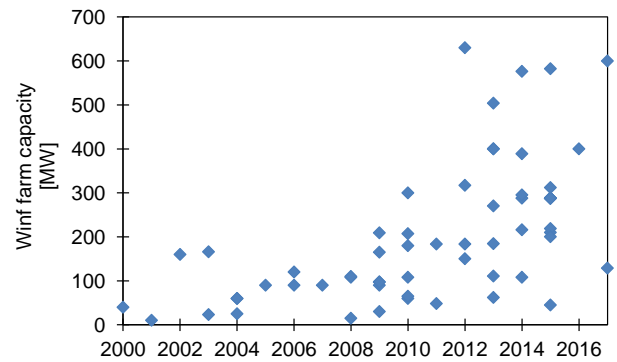


Figure 2. Development of project sizes of European offshore wind power plants between 2000 and 2017 (year of commissioning)

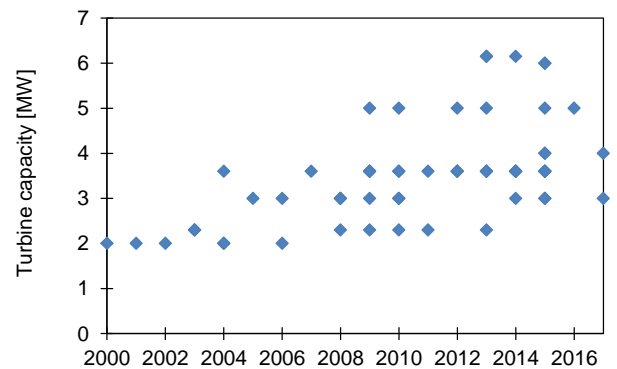


Figure 3. Development of turbine sizes of European offshore wind power plants between 2000 and 2017 (year of commissioning)

B. Distance to shore and water depth

Most commercial offshore wind power plants operating to date are installed within 20 kilometres to shore at a water depth of no more than 20 metres. The average distance to shore between 2000-2009 has been 10.0 kilometres, and the average water depth 9.6 metres. This has increased to averages of 37.7 kilometres and 22.7 metres for the power plants commissioned from 2010 onwards. Of the currently operating wind power plants, the project BARD Offshore 1 stands out with being 90 kilometres from shore at a water depth of 40 metres. In 2016, Global Tech I will come online, which is 115 km from shore at 38-41 metres water depth.

In the most recent developments (projects under construction in 2015), distances to shore and water depths rise sharply, as illustrated in Fig. 4 and Fig. 5. One can maybe speak of a second era of offshore development.

¹ The equation is logarithmic specified; the dummy is used until 2009 to handle the change in wind turbine supply conditions.

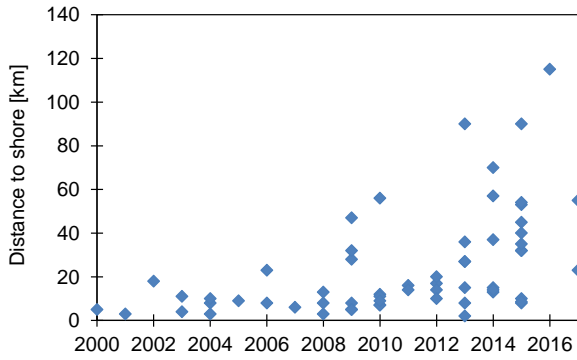


Figure 4. Development of distance to shore of European offshore wind between 2000 and 2017 (year of commissioning)

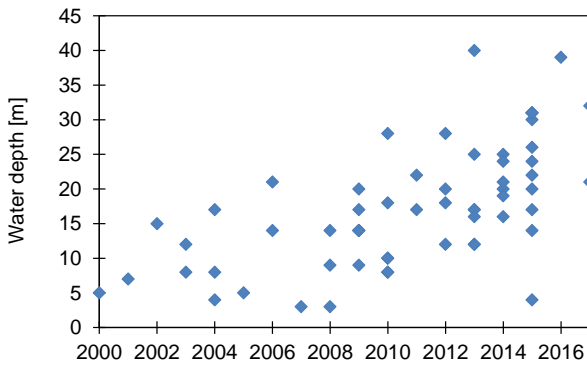


Figure 5. Development of water depth of European offshore wind between 2000 and 2017 (year of commissioning)

Distance to shore and water depth are of significant economic importance, because they influence both the investment costs and the operation and maintenance costs.

Increasing distance to shore affects mostly installation costs and grid connection costs. Installation costs increase because of two elements. Firstly, the travelling time from the holding port to the site increases. Secondly, tougher weather conditions make the installation more difficult. This issue is often referred to as ‘weather downtime’, where offshore operations are at a standstill. This downtime is usually 20-30 % [13]. During these times, often the installation vessels and crews have to be held at a stand-by, which is costly. Grid connection costs increase because of increased length of the export cable. Export cables (including installation) cost between 0.5 and 1 million Euro per kilometre, so these costs are estimated to increase linearly with increasing distance to shore [13].

Increasing water depth affects mostly foundation costs. Foundation costs (including installation) are estimated at around 1.5-2 m€/MW in shallow waters and to rise exponentially with increasing water depth [13].

Utilising regression analysis, a significant relationship is found for the two variables together, distance to shore and water depth. For both, the coefficient is around 0.1, indicating that a 10% increase in either water depth or distance to shore will imply a 1% increase in specific investment costs. In general, the coefficient for water depth

is best determined and is statistically significant. Due to multi-collinearity between the two variables it is, however, not possible to separate them. This is due to the fact that in practice distance to shore and water depth are connected: typically the farther from shore, the deeper the waters.

The connection between distance to shore and water depth can also be seen when comparing the simple averages over the wind power plants for different levels of both factors, as in Table III.

Fig. 6 illustrates the relationship of distance to shore and water depth with the specific investment cost. There are no wind power plants with a high distance to shore and at the same time low water depth or vice versa. We find that (as expected) the cost tends to be larger the higher the distance to shore and water depth (indicated by the size of the circle).

TABLE III. SPECIFIC INVESTMENT COSTS OF EUROPEAN OFFSHORE WIND POWER PLANTS, AVERAGES FOR DIFFERENT LEVELS OF DISTANCE TO SHORE AND WATER DEPTH, IN M€/MW

<i>Distance to shore</i>		<i>Water depth</i>	
0-10 km	2.5	0-10 m	2.2
11-20 km	3.3	11-20 m	3.3
>20 km	3.9	>20 m	3.9

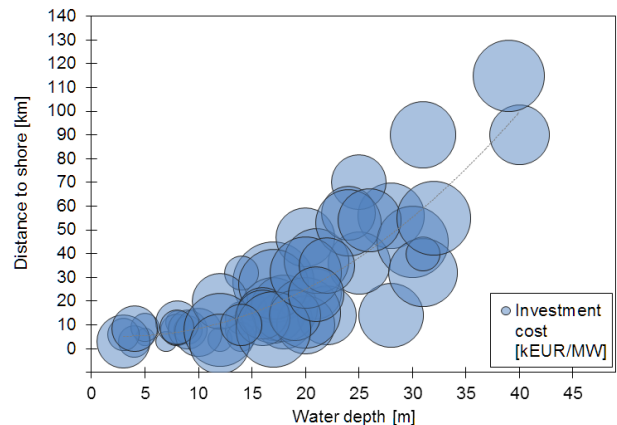


Figure 6. Relationship between distance to shore and water depth, and influence on specific investment costs of European offshore wind power

VI. COST DEVELOPMENT - THE PAST AND THE FUTURE

Future costs have always been difficult to predict. This is especially the case in the offshore wind industry, where previous expectations about cost reductions from the late 1990s and early 2000s have actually given way to cost increases [14]. While future cost projections often rely on expectations related to technology development and operational cost optimisations, there are many additional factors that can influence the overall development. In a study of the significant price increases of offshore wind in the UK between 2005 and 2010, the major cost drivers are identified as (in descending order of impact): 1. Materials, commodities, labour costs; 2. Currency movements; 3. Increasing prices for turbines (in addition to cost of materials) due to supply chain constraints, market conditions, and engineering issues; 4. Increasing water depth and distance to shore; 5. Supply chain constraints (in vessels and ports); 6. Planning and consenting delays [14].

In any case, the offshore wind industry is optimistic towards the future cost developments and expects significant cost reductions during the next ten years: An industry survey by [9] with 200 executives from the European offshore industry revealed that investment cost reductions at on average 23% are expected until 2023. In several addresses at the EWEA Offshore in 2013, it was argued that the industry is on track to achieve the targets of 40% cost reduction by 2020. A study for the German offshore wind sector by [12] came to the conclusion that cost reductions of up to 39% of the levelised costs can be achieved over the next ten years under optimum market conditions.

The most important drivers for future cost reductions in the offshore wind supply chain are identified to be economies of scale, higher capacity turbines, and technology innovation [9]. Additionally, improvements in logistic infrastructure such as geographic concentration of the supply chain and access to faster ships can play a role [12].

The different factors induce reductions in different cost components. In respect to the investment cost components, it is expected that the three largest elements (turbines, installation, foundations) are also the ones with the highest cost reduction potentials, namely 5% to 7% each in the short term [9]. Turbine costs are expected to mainly be reduced through economies of scale. Higher capacity turbines are one element in this. Currently, the largest installed turbines have a capacity of 6.15 MW (mid 2015). In the near future, we expect to see 8 MW and even 10 MW turbines being installed in European waters. Also, greater competition in the offshore wind turbine sector can be expected along with the maturing of the market.

Regarding installation costs, it is expected that a more efficient installation process alone could result in a 1.65% decrease of total investment cost [9].

Foundation costs are expected to be reduced through economies of scale, higher capacity turbines, technology innovation, and standardisation of foundation designs [9]. Also, a holistic design optimisation can contribute to minimizing overall costs. Recently developed jacket-based foundations can e.g. be installed within 12 hours, rather than in up to five days which are typically required for a monopile foundation. Thus, foundation design can significantly influence installation costs as well. Longer

term cost reduction options in investment costs are high voltage direct current (HVDC) connections to shore and even offshore grid networks, which will benefit multiple offshore wind power plants at a time.

On the operations side, potentials for O&M cost reduction and performance optimisation are expected to come from mainly three drivers: reliability, maintainability and operations management [10]. The reliability of offshore wind is expected to improve from advanced condition monitoring and failure avoidance. Concepts for increasing the maintainability could e.g. include a minimisation of the need for jack-ups during repairs. Improvements in operations management could include a condition-based maintenance and scheduling of activity. Due to the highly specific O&M cost for offshore wind, cost reduction potentials are difficult to quantify on a general basis.

VII. DISCUSSION AND CONCLUSIONS

Above, we have discussed the past and the future of offshore wind economics from the cost side, both for investment costs and for operation and maintenance costs. Other costs, such as fuel costs and cost of CO₂ emissions that may be substantial cost drivers of fossil-fuelled power plants are not so relevant for offshore wind. In this, the economics of offshore wind (and other fuel-free technologies) is fundamentally different from the economics of fossil-fuelled power plants.

With our focus on the cost side, we do not consider the full price of introducing offshore wind (or any other technology) into the power system. Integration of wind power into the overall energy system implies additional costs, dominated by two main aspects: balancing needs and grid infrastructure [15]. Finally, offshore wind also has a price-decreasing effect on the wholesale market. Hence, we here only shed light on one aspect of the economics of offshore wind.

Nevertheless, we can conclude that the economics of offshore wind has changed drastically since the first wind power plant has been built in European waters in 2000. Specific investment costs have increased substantially, from on average 2.1 m€/MW in the first decade of the century, to 3.7 m€/MW for wind power plants commissioned from 2010 onwards. This 70% increase in specific investment cost goes along with increases in distance to shore and water depth of on average 280% and 140%, respectively.

According to industry expectations, a significant potential seems to exist for further cost reductions through economies of scale, technology innovation and improvements in logistic infrastructure. If these cost reductions will be sufficient to counterbalance cost increases from moving longer from shore and into deeper waters, remains to be seen.

Further analysis can help to better predict overall cost developments for the future. This could be done by extrapolating trends from the data set. Future research and development can with benefit also focus on how the cost reduction potentials can in practice best be exploited.

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