Future Cost of Onshore Wind

Recent auction results, long-term outlook and implications for upcoming German auctions

ANALYSIS

Agora Energiewende

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IMPRINT

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Preface

Dear Reader,

The costs for electricity from renewable generation have been falling significantly in recent years, and record low bids at auctions around the world have grasped the attention of the public. Solar photovoltaics and offshore wind auctions, in particular, have attracted a lot of interest. The results for onshore wind, however, are just as impressive.

The future cost development of onshore wind is of great relevance, since it is a key pillar of the energy system transformation in many parts of the world. However, the estimated long-term cost reductions vary significantly, as different studies value the cost drivers of wind differently.

In Germany, the opaque and complex cost structure of onshore wind is the root of much controversy. International auction results with winning bids of less than half of the typical German pay rate left people questioning the costs of domestic wind power. However this discussion often fails to account adequately for differences in the quality of wind resources. In light of the upcoming, and first, German onshore wind auctions, we aim to contribute to the ongoing discussion by providing the necessary context for international auction results, a general outlook on the future cost of onshore wind, and by illustrating the existing potential and hindrances for cost reductions in the German market.

I hope you find the analysis inspiring and enjoy the read! Comments are very welcome.

Yours sincerely,

Patrick Graichen,
Executive Director of Agora Energiewende

Findings at a glance

1. **Wind power costs are coming down, as auction results around the world show:** in Morocco, Peru and Mexico, average winning bids ranged between 2.7 and 3.4 EUR ct/kWh in 2015/2016. This fundamental cost reduction trend is projected to continue.

2. **The larger wind turbines are, the cheaper they produce electricity.** The size of windmills is expected to be the major driver of future cost reductions, as costs for increasing turbine size grow at lower rates than the benefits. The limits to onshore turbine growth are most likely not of a technological nature but rather a question of local political consent.

3. **In Germany, projects at excellent wind sites can be built with only slightly higher generation costs than the most cost efficient auction-winning projects throughout the world.** The levelized cost of electricity at those sites ranges between 3 and 4.5 ct/kWh for turbines of the latest generation. Major potentials to further improve cost efficiency are reducing land and maintenance costs, which are far higher than the international average.

Contents

Introduction

Wind energy, together with solar photovoltaics (PV), is a key pillar of the transition from fossil fuels to sustainable generation in the power sector. Wind energy currently accounts for 3.7 per cent of global power production, and capacity growth is continuing at a rapid rate.[1] In 2016, total installed capacity jumped to 467 GW as 51 GW of new wind capacity was added across the globe.[2]

Wind power has become a very competitive energy source that is able to compete with fossil fuels in many parts of the world, with projects with costs as low as 2.7 ct/kWh and projects regularly achieving costs of 3.6 ct/kWh[3]. In the US, for example, it is the cheapest source of electricity even without subsidies. The lowest levelized cost of electricity (LCOE) from wind energy undercuts the lowest LCOE from gas by almost 2 ct/kWh, from coal by 3 ct/kWh and from nuclear by nearly 6 ct/kWh.[4]

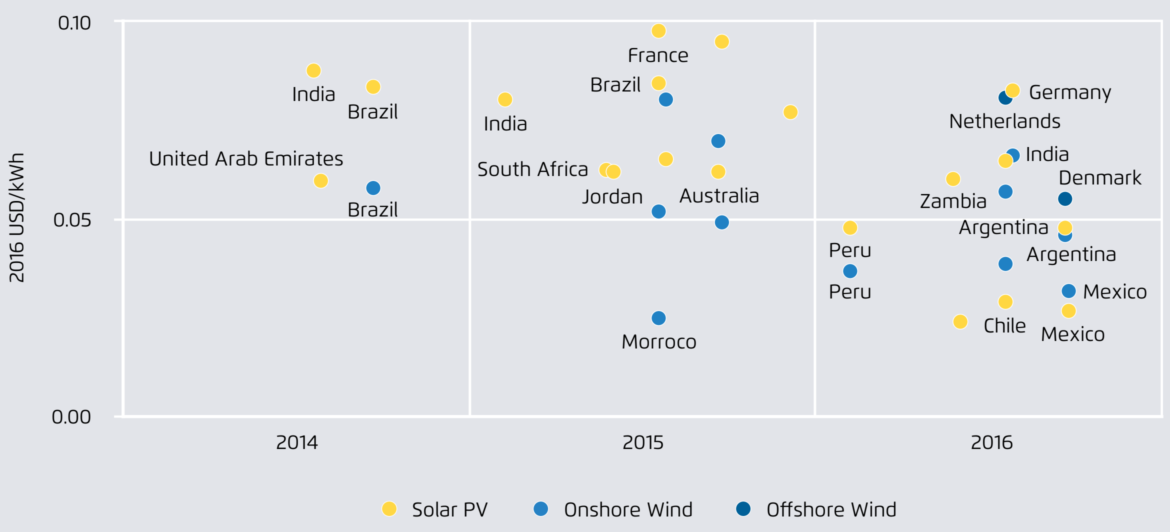
1 REN21 (2016)

2 IRENA (2017a)

3 IRENA (2017b). All prices are in real 2014 euros and rounded to two significant figures, if not declared otherwise. We have used the annual average dollar–euro exchange rate in 2015 and 2016 of 0.9 when converting monetary figures.

4 Lazard (2016). Wind: 2.9–5.6 ct/kWh; Gas CCGT: 4.3–7.0 ct/kWh; Coal: 5.4–12.9 ct/kWh; Nuclear: 8.7–12.2 ct/kWh. As a simple measure of cost, LCOE does not account for the variable nature of wind and PV as compared to the more stable output of nuclear power. Yet it has been shown that a reliable energy system based on wind and solar can be 20 per cent cheaper than one based on new nuclear power, when the necessary backup technologies is included in both cases. For this analysis, the cost of nuclear power was drawn from the Hinkley Point C agreement in the UK (Prognos 2014).

Worldwide auction results for onshore wind, offshore wind and solar PV from 2014 to 2016 in USD/kWh — Figure 1



IRENA (2017b)

While recent auction results for offshore wind[5] and solar PV have garnered much attention, onshore wind auctions held in Peru, Mexico and Morocco have shown that project developers and investors remain convinced of their ability to provide energy at ever lower cost in the future (Figure 1). New record bids were recorded, with one Moroccan bid going as low as 2.2 ct/kWh for one specific location.[6]

Investor confidence in future cost reductions is vital for the continued development of global wind energy. While the sharp fall in solar PV prices is expected to continue,[7] it is important for wind to stay competitive. But how comparable are onshore wind auction results from one country to another, given that factors such as local wind resources, cost of capital,[8] and local cost structures are highly country specific? And what are the expectations regarding their long-term development?

This paper aims to shed light on these important questions. In section 1, we discuss anticipated long-term cost trends and technology developments. In section 2, the record-breaking Moroccan auction results from late 2015 are analyzed and put into context. Section 3 provides an impression of progress in Germany by comparing the generation costs of German projects commissioned in 2012/2013 and 2016/17. In section 4, we explore the extent to which the low prices achieved in Morocco are indicative of potential future trends in Germany. In the final section, we offer an outlook on the first German onshore wind auction in 2017.

5 The German auction resulted in an average bid of 0.44 ct/kWh. Several winners did not claim any support. Reasons are seen in the oversupply of planned projects, no grid connection charges, the long time horizon until realization which allows for future technological developments and a bet on suffciently high market prices associated with an anticipated coal phase out. (Bloomberg 2017)

6 Reneweconomy (2016)

7 Fraunhofer ISE (2015)

8 Many renewable energy technologies are capital cost intensive, since they have very low operational costs. High financing cost is a major hindrance to their deployment, even in regions with great resource potential. In particular, elevated country risk may often drive up financing costs. It is a problem that exists even inside the EU, with renewable energies struggling to get off the ground in several south-eastern European countries (IRENA 2017c). See appendix, chapter Cost of Capital.

1 Long-term Cost Trends

Several studies focus on the future cost of wind energy, using different approaches to estimate the effects of cost reductions in various areas, including technological innovation, cheaper system components, improved manufacturing procedures and projected capacity-factor increases. Two studies estimate that LCOE reductions up to 2025 will range from 5 per cent to 26 per cent. The time frame beyond 2025 remains unaddressed by most investigations. One notable exception is a study that expects a cost reduction of roughly 25 per cent by 2039 – however, this work fails to provide detailed explanations (table 1).

In this way, we find large divergence in existing forecasts. One problem is that the assumptions behind the models often remain unclear. In many cases, for example, one does not know to what extent learning curves were applied or what other methodology the models are based upon.[9]

9 A classical learning curve approach might be vulnerable to error because it concerns learning with the deployment of the same product. Since wind turbines continuously increase in size, manufacturing repeatedly faces new challenges, meaning the production process continuously changes (Nordhaus 2008).

A recent analysis offers a higher degree of transparency while also considering a longer time frame. In a novel elicitation survey, 163 experts were asked about the future potential for cost reductions in the LCOE for wind power.[10] The participating experts worked in research and development, project planning, manufacturing, non-profit organizations and governmental agencies. The results from this survey are shown in Figure 2. In the median scenario – that is, under circumstances consistent with past trends – the experts estimated an LCOE reduction of 24 per cent by 2030 and 35 per cent by 2050. In the low scenario – that is, under favourable conditions for research, development and deployment – they anticipated an LCOE reduction of 44 per cent by 2030 and 53 per cent by 2050.

Cost Reduction Drivers and Anticipated Developments

The survey asked experts to name factors that could lead to a high, median or low LCOE trend. The median and low scenarios were associated with technical advancements such as larger rotors and higher towers as the drivers of cost reductions; whereas the high

10 Berkeley Lab et al. (2016), see the appendix for details.

LCOE reductions according to existing studies — Table 1

Estimated LCOE Reduction	Until	Main Drivers	Study
Roughly 5.5 %	2025	Innovation	KIC InnoEnergy (2014)
Up to 26 %	2025	Component cost, manufacturing procedures, increased capacity factors	IRENA (2016)
Roughly 25 %	2039	Not explained	BNEF (2017)

own compilation

scenario was explained by weak demand for new wind power capacity, the depletion of higher quality sites for wind turbines and lack of investment in new transmission grid to access those sites.

Continuous Upscaling

Larger rotor diameters and lower generator–rotor ratios will have the greatest impact on bringing down the cost of wind, according to the survey. The experts do not expect the upper boundaries of nameplate capacity to be pushed much further, which hints at a continuing shift toward less attractive sites.

Especially in Europe, where the best locations are mostly taken, greater rotor diameters and higher hub heights can be used to install greater capacities at sites with poor wind conditions.[11] Developing turbines suited for IEC wind classes III and IV[12] will therefore continue to become more relevant, as this will open up new sites closer to urban and metropolitan areas, where greater capacity is actually needed.

11 In early 2017, Enercon started operating the first E-141 EP4, probably the world's largest onshore turbine to date. It is a low wind turbine designed for wind class III with a nameplate capacity of 4.2 MW and a rotor diameter of 141 meters.

Maintenance Costs

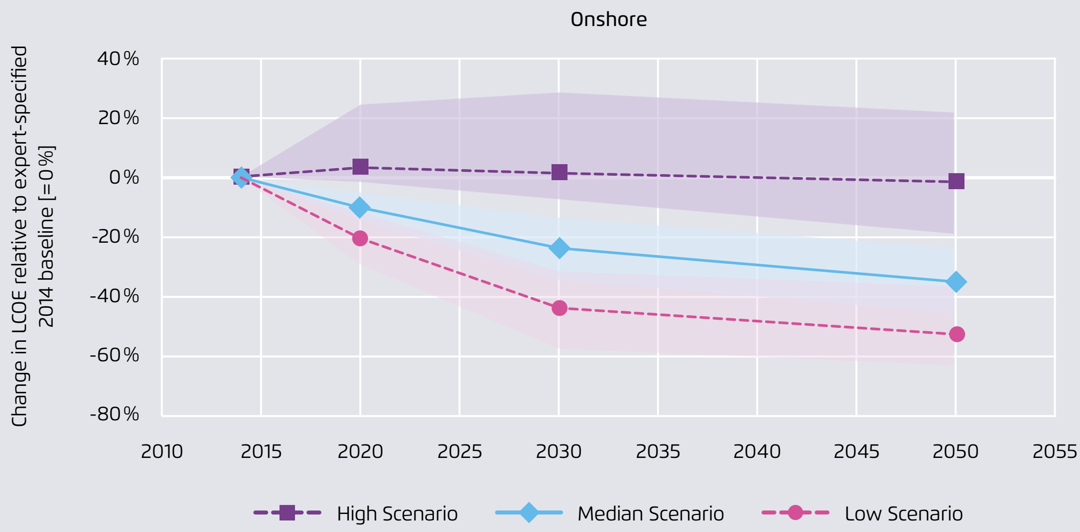
While the surveyed experts did not emphasize the issue of maintenance costs, other studies have found maintenance to be an important factor that has a strong potential for improvement. Maintenance costs vary significantly between different countries and regions. Operation and maintenance costs comprise up to 2.3 ct/kWh of LCOE in Europe yet only 0.9 ct/kWh in the US.[13] In general, such costs are responsible for 15 to 25 per cent of LCOE.[14]

12 International standard defined by the International Electrotechnical Commission (IEC). Wind classes III and IV are equivalent to average annual wind speeds of 7.5 and 6 meters per second (IEC 61400)

13 IRENA et al. (2016)

14 IEA (2013)

The expected change in onshore wind LCOE up to 2050 relative to an expert-specified 2014 baseline — Figure 2



Median: circumstances consistent with past trends.
Low: favourable conditions for research, development and deployment.
High: weak demand, depletion of higher quality wind resources and lack of investment in transmission grids.
Note: The shaded areas correspond to the 25th and the 75th percentile of responses for each scenario. adapted from Wiser et al. (2016).

These high maintenance costs are often attributed to the fact that wind turbines are still a relatively new technology, combined with unmanned operation. Operators have begun taking measures to lower costs, such as round-the-clock remote monitoring with improved sensor technology. Advanced wind flow measurements to predict gusts as well as proactive and reactive adjustment of the rotor are also promising innovations that could help to reduce maintenance expenses.[15]

The International Energy Agency (IEA) has started collecting data to build a publicly available databank that will help operators to implement improved maintenance strategies. Furthermore, with increasing competition in the maintenance sector, substantial cost reductions can be expected.[16]

15 BWE (2016), KIC InnoEnergy et al. (2014), EAWE (2016)

16 BWE (2016)

2 Auctions with Low Price Outcomes

Numerous recent auction results for offshore wind projects have attracted attention for the low price of winning bids, particularly in Denmark and the Netherlands.[17] In Denmark, bids as low as 5.0 ct/kWh were accepted in the Danish Kriegers Flak[18] auction (table 2).

Onshore wind auction results are just as impressive. One of the recent highlights was the Moroccan auction from late 2015, which concluded with an average of 2.7 ct/kWh,[19] and saw bids going as low as 2.2 ct/kWh for one specific location.

Record low auction results are not only an indicator of how competitive wind energy already is, but also show that investors have confidence in the development of this technology. Since all of these projects will take years to be realized, future developments are already being factored in.[20] It is important, however, to put these results into perspective, since there are many factors that can differ by project and country. Also, a winning bid is not equal to a realized and profitable project.

For many of the auctions listed here, the available information is quite scarce. The specific bids as well as further details about the winning projects, such as locations and specific capacities, are often not disclosed. The Moroccan auction of late 2015 is comparably well documented, which is why we will have a closer look at it here, to illustrate which circumstances are helpful for achieving low LCOEs for wind and how low-auction results around the world come about.

The Moroccan Auction

In late 2015, Morocco held an auction for the development of 850 MW of onshore wind, which resulted in the very low prices mentioned above. In addition

17 The German offshore results are difficult to compare to other auctions for a variety of reasons, as listed in footnote 5.

18 Vattenfall (2016)

19 Reneweconomy (2016)

20 For example, in the Kriegers Flak bid, Vattenfall factored in future turbine development, counting on 10 MW turbines being launched in time for the realization of the project (Energate 2016).

Wind auction results Table 2

		Average Bid in Euro ct/kWh	Quarter
Offshore	Borssele I & II (NL)	7.2	Q3 2016
	Danish Near Shore (DK)	6.4	Q3 2016
	Kriegers Flak (DK)	5.0	Q4 2016
	Borssele III & IV (NL)	5.5	Q4 2016
Onshore	Morocco	2.7	Q4 2015
	Peru	3.4	Q1 2016
	Mexico	3.0	Q3 2016

own compilation

to excellent wind conditions, concessional finance – i.e. flexible long term loans with rates far below the market[21] – helped to achieve this exceptional result.[22] The winning bid was placed by a consortium consisting of Enel Green Power, Siemens and the Moroccan energy company Nareva, which is owned by King Mohammed VI. Four of the five sites are located in coastal areas, directly profiting from Atlantic trade winds and accounting for 700 of the 850 MW awarded. Two of them, Boujdour and Tiskrad, are located in the Western Sahara. The commissioning of the project is expected between 2017 and 2020.[23]

Context of the Results

To help classify the results of the Moroccan auction, we try to reconstruct the associated generation costs[24] for each location. This reconstruction uses German data for capital expenditures and financing costs[25], as well as international reference figures for operation and maintenance costs.[26]

21 Blackwell (2017)

22 Reneweconomy (2016)

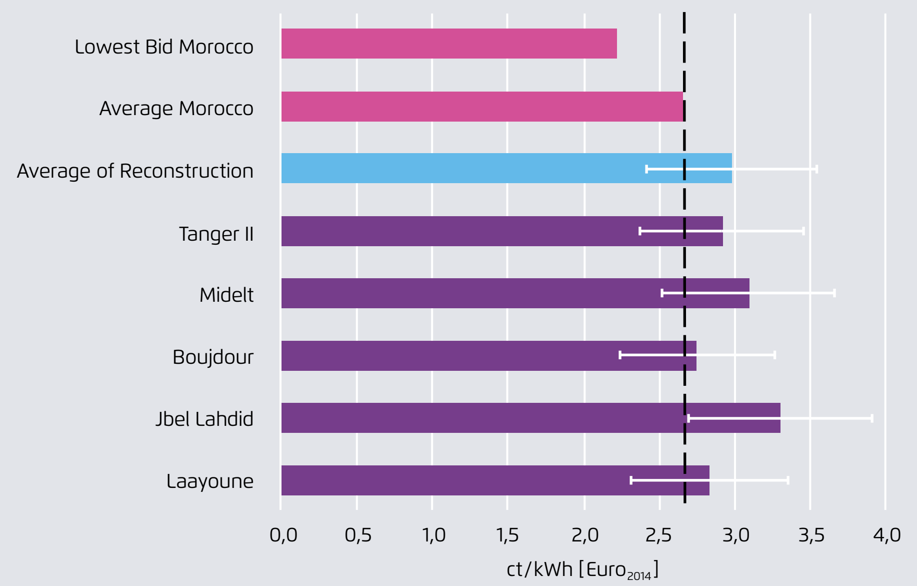
23 Reneweconomy (2016)

24 By applying the *simple LCOE* formula (NREL 2016).

25 These cost data are drawn from a survey commissioned by the German Wind Energy Association (BWE) in 2013 and the updated version from 2015, which included 71 wind parks consisting of 317 wind turbines and 663 MW (Deutsche WindGuard, 2015). It provides average results for investment and operating costs as well as their standard deviation and average generation costs of those wind projects at sites of different quality. The turbine cost is based on an analysis of 47 different turbine types that cover 97 per cent of the German market.

26 We assume O & M costs to be 2 per cent of the total capital costs for big turbines, which is the upper end of a range of 1.5 to 2 per cent provided by IRENA (2016). In comparison, German O & M costs are quite high.

Moroccan auction results (lowest bid and average) and reconstructed results (average and individual sites) Figure 3



Note: Error bars for the reconstructed sites result from the underlying cost data's standard deviation.

Given that Siemens is part of the winning consortium in the Moroccan auction, we base our evaluation on the Siemens SWT-3.6-130 turbine (which has a 3.6 MW nameplate capacity, 130 meter rotor diameter, and 135 meter hub height). Developed for IEC wind class II with a reference speed of 8.5 meters per second, it is one of the largest existing onshore wind turbines and will serve as a benchmark for other comparisons in this paper.[27] The results that can be achieved with other large turbines of the latest generation – such as the Vestas V126 3.45, the GE 3.4-137 or the Gamesa G132 3.3 – deviate only slightly from the ones presented here.

Annual wind speeds at the five locations are between 7.7 and 10.3 meters per second at a height of 200 meters.[28] The best wind conditions can be found at the two sites located in the Western Sahara, which boast wind speeds above 10 meters per second. This means the selected turbine would reach between 4100 and 5000 full load hours at all five locations, with 4600 full load hours on a capacity weighted average. Such a high number of full load hours reflects the extraordinary wind conditions present on the Moroccan Atlantic coast.

→ Our calculations yield an average LCOE of 3.0 ct/kWh. The lowest result (2.8 ct/kWh) was calculated for the wind park that is to be installed near the Moroccan coast in Boujdour (see Figure 3).
→ The actual auction results of 2.7 ct/kWh on average and 2.2 ct/kWh for the lowest bid are within the standard deviation of our estimates.
→ That is, if wind resources in Germany were as good as in Morocco, one could reach similar LCOE results.

27 Siemens (2016a). It is very likely in the case of at least two Moroccan projects that Siemens will *not* deploy the SWT-3.6-130, but the new high wind turbine they will launch in the near future. Since there are no technical data available yet, an evaluation can only be done with the SWT-3.6-130.

28 According to the IRENA Global Wind Atlas developed by DTU Wind Energy. See: http://irena.masdar.ac.ae/

3 Cost of Electricity Generation for German Projects

The cost of wind energy is continuously declining, and modern wind turbines are already capable of producing power at substantially lower costs than their predecessors. Large turbines are the most cost efficient and perform considerably better than the average. This section spotlights the decline in German wind LCOEs between 2012/13 and 2016/17.[29] It also compares German LCOE figures with LCOE calculations for the SWT-3.6[30] wind turbine to provide context and to demonstrate the cost advantage of larger turbines.[31]

29 Deutsche WindGuard (2015), cost data for 2016/17 is based on planned projects to be commissioned at that time.

30 In the German market, other turbine models and manufacturers are predominant. The SWT-3.6's role in this paper is to facilitate the comparison between the Moroccan and the German cost structures.

31 The same cost data presented in section 2 were used with the exception of data on operation and maintenance, which were calculated using the German figures provided in Deutsche WindGuard (2015).

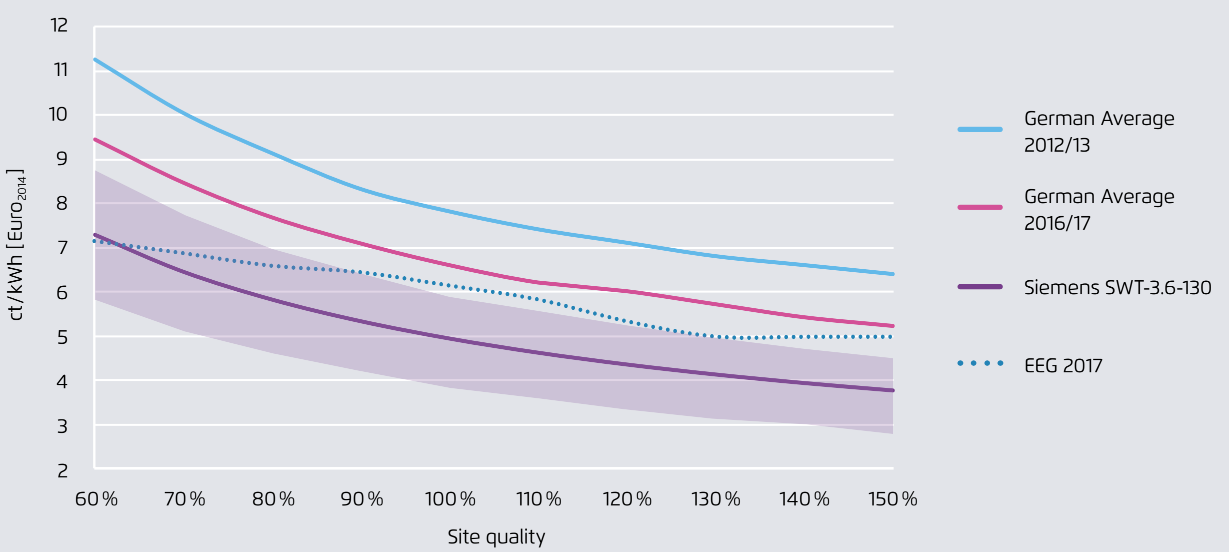
Figure 4 shows generation costs at wind sites of varying quality, ranging from 60 to 150 per cent of a defined reference site,[32] which corresponds to wind speeds of roughly 5.5 to 9.5 meters per second at hub height in the case of the SWT 3.6.[33] It includes the

32 We used the German "reference yield model" (*Referenzertragsmodell*) foreseen under EEG 2014 to achieve comparability between the generation costs presented in the survey. This model couples the level of remuneration to the quality of the wind site (BWE 2016a). The model was put into place to incentivize the deployment of wind turbines at lower quality sites. It defines a reference site as 100 per cent and uses this site as a metric for comparing projects and adjusting remuneration.

33 Relative site quality in per cent is turbine dependent, since it refers to the energy production of the turbine in question at a given reference site.

Electricity generation costs for projects in Germany in 2012/13 and 2016/17 and for the Siemens SWT 3.6-130, as well as the EEG 2017 pay rates

Figure 4



Note: The shaded area represents the standard deviation resulting from the variance of the input cost parameters in the underlying survey. A 150 per cent site means that a given turbine at this site produces 1.5 times the energy it would produce at the reference site. The EEG pay rates are deflated using an annual inflation rate of 2 per cent. Deutsche WindGuard (2015) and own calculations.

feed-in remuneration granted by EEG 2017, which applies until the start of German wind power auctions in 2017.

- → The LCOE curves show a substantial cost decrease of more than 1 to almost 2 ct/kWh from the average project in 2012/13 to the average project in 2016/17.
- → The cost advantage we calculated for turbines of the latest generation is even larger: The SWT-3.6 is able to produce for 1.5 to 2 ct/kWh less than the average in 2016/17 and for more than 2.5 to 4 ct/kWh less than the average in 2012/13. However, these figures do not take into account that this turbine model achieves a higher number of full load hours at poorer sites than older turbines, meaning that even larger cost reductions than these estimates could be expected in real-world conditions at those sites.[34]
- → The pay rates provided according to EEG 2017 are around 1 ct/kWh higher than the LCOE estimate for the SWT-3.6 at sites of more than 90 per cent. The difference is greatest at high quality sites, where the remuneration is 25 per cent higher than the generation cost.
- → Compared to the average project commissioned in 2016/17, however, we can clearly see an EEG remuneration shortfall across the entire range of sites. This shortfall is greatest at sites with a wind quality rating below 85 per cent.[35] While projects commissioned in 2016/2017 enjoy the higher feed-in rates provided by EEG 2014, the data nevertheless show that the average project commissioned today in Germany would not be profitable under the EEG 2017 transitional regulation.

34 For example: A site rated at 60 per cent compared to the reference site with an older turbine would have a higher rating with the SWT-3.6. With its great rotor diameter, higher hub height and lower specific power per rotor area, it yields energy more constantly at lower wind speeds.

35 The average quality of new sites in Germany 2013 was between 70 and 80 per cent (Deutsche WindGuard 2015).

4 How Comparable are Moroccan Auction Results with German Wind Projects?

Comparing international wind auctions and individual projects is tricky, given the variance in cost structures, including initial capital expenditures, ongoing operation and maintenance costs, and grid connection outlays. In addition, the availability of good sites, building regulations and other factors vary considerably between countries. Accordingly, this section only aims to place the information presented earlier in proper context. It does not claim to accurately describe in detail the costs of existing wind projects. Rather, building on sections 2 and 3 an attempt is made to compare the results of the Moroccan auction to the typical German cost structure.

Figure 5 shows the calculated LCOE for the SWT-3.6 at German sites drawn from section 3 and applies the future relative cost developments from the expert survey presented in section 1 (median and low scenario):

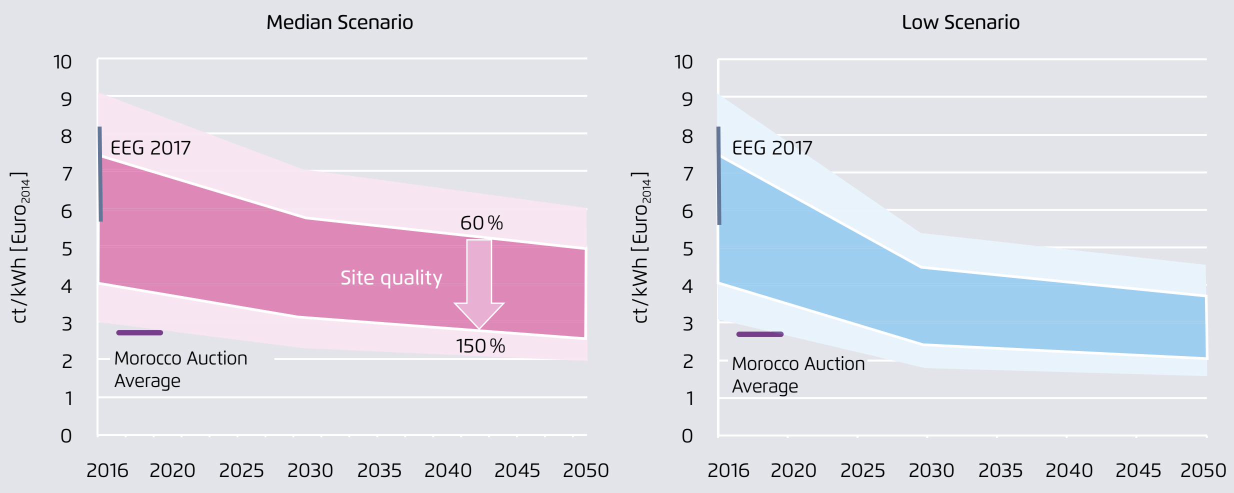
Today, the LCOE ranges from about 4 ct/kWh at very good sites (150 per cent) to about 7.5 ct/kWh at low quality sites (60 per cent). If we include the standard deviation for cost parameters,[36] the range gets even wider – from 3 to 9 ct/kWh. The remuneration for these sites according to EEG 2017 is between 5.6 ct/kWh (130 per cent site and better) and 8.2 ct/kWh. By comparison, Figure 5 also contains the average accepted bid in Moroccan projects.[37]

36 A measure of variance in input cost parameters in the underlying survey.

37 Recall that the Moroccan bids already take into account expected future cost reductions.

Projected German onshore wind costs based on the median and low scenarios and Moroccan auction results

Figure 5



Note: Figures are in real 2014 euros. Shaded regions represent the standard deviation for German cost data. The Moroccan projects are expected to be commissioned between 2017 and 2020.
Own calculations for the SWT-3.6 as a representative modern wind turbine, derived from Deutsche WindGuard (2015) for current cost levels at German sites of different quality (60 to 150% of reference site) and from Wiser et al. (2016) for future cost projections.

- The median scenario estimates generation costs for state-of-the-art turbines to be between 3 and nearly 6 ct/kWh in 2030, and between 2.5 and 5 ct/kWh in 2050.[38]
- The low scenario leads to more optimistic cost reductions, with LCOEs ranging between 2.5 and 4.5 ct/kWh in 2030 and between 2 and just over 3.5 ct/kWh in 2050.
- If we assume cost decreases according to the low or median scenario based on the expert survey presented in section 2, we see the Moroccan auction results ranging close to the bottom edge of the standard deviation for a German project that uses the turbine in question (Figure 5).

These calculations indicate that there will be some projects realized in Germany by 2020 that will produce electricity at a cost not much higher than the Moroccan projects. Such projects will be the exception, however, as average costs will be higher. Prerequisites for below-average LCOEs are better wind resources, lower investment/maintenance costs, or lower capital costs. If German maintenance costs were reduced to the international average, this change alone would dramatically narrow the gap to the Moroccan LCOE.[39]

Considering Siemens is part of the consortium that won the Moroccan auction, it is conceivable that the turbine costs for the Moroccan project are lower than they would be in an average German project. The high volume of turbines (850 MW) being deployed means significant equipment cost reductions due to economies of scale. Furthermore, concessional finance reportedly played a role in the auction, reducing cost of capital. However, these considerations cannot be evaluated empirically due to a lack of available information.

38 These results concur with the 2050 LCOE estimate for wind of 3.9 ct/kWh produced by Acatech, 2016.

39 Compare to section 2.1.1. where the assumption for average international projects were used to reconstruct the LCOEs. The auction results were within the margin of uncertainty of the reconstructed LCOEs.

5 Can we expect a Record-Low Bid at the First German Onshore Wind Auction?

No one can accurately forecast how low the winning bids of the first German onshore wind auction will be. However, it does not seem likely that they will come close to the outcomes witnessed in Morocco, Mexico or Peru. As sections 2 and 3 show, good wind conditions are one of the key drivers of low costs. Since onshore wind energy has already been deployed in Germany for decades, the best sites with the highest annual wind speeds are already taken. Additional factors could be a higher cost of capital than that witnessed under the EEG financing system, due to elevated risks associated with the auction process[40], or differences in grid connection costs.

Cost Reduction Potentials

Cost reduction potentials are primarily evident with a view to land and maintenance costs. While there are no studies that show a comprehensive picture of the cost of land in Germany, it is generally accepted that rents are excessively high. Reports suggest payments of an average of 50,000 to 70,000 euros and up to 100,000 euros per turbine and year.[41] Not only private landowners profit from such exorbitant leases. Since the priority regions for wind power include state forests and other types of publicly owned land, public landlords have been using this opportunity to consolidate their budgets.[42] The pressure exerted by the auction process might not be able to reduce these costs in the first round. However, we can expect drastic reductions in the long run, since such high payment levels cannot be maintained in a competitive environment.

Operation and maintenance costs are responsible for between 1.7 ct/kWh and 2.2 ct/kWh in Germany.[43] This cost level is 70 to 120 per cent higher than the US average[44]. Since there are ambitious measures being undertaken to lower costs in the maintenance sector, even further cost reductions can be expected in the future. These measures include the standardization of maintenance information for the implementation of a databank, as well as improved monitoring and damage diagnosis.[45]

Regulatory Barriers

Even though the quality of the wind resource is of major importance for reaching low costs, the German government has restricted the deployment of wind turbines exactly where the majority of the country's high wind sites are located. In this region of northern Germany, large-scale turbine deployment and insufficient transmission grid development lead to frequent bottlenecks, and grid operators have to frequently curtail production. To address this problem, the government has imposed limits on the addition of new capacity in the so-called "grid expansion area." The annual addition of new capacity is currently limited to 58 per cent of the average expansion over the three previous years.[46]

Another issue in Germany is that various regulations hinder the optimal exploitation of available wind resources. In some German districts, mainly in Saxony, restrictions limit the maximum turbine height to

40 Deutsch et al. (2014)

41 Coerschulte (2014), Handelsblatt (2013)

42 Handelsblatt (2013)

43 Own calculations based on Deutsche WindGuard (2015)

44 See Maintenance Costs in section 1

45 See the Operation and Maintenance chapter in the appendix.

46 Agora Energiewende (2017)

100 meters, including the rotor.[47] This prevents larger, more cost efficient turbines from being installed. In modern turbines, the rotor diameter alone is often significantly larger than 100 meters. In addition, distance regulations have been drastically impeding the implementation of new wind projects in some German regions. For example, the 10-H rule that Bavaria introduced in late 2014 requires wind turbines be installed at a minimum distance of 10 times the turbine height from inhabited areas, which can amount to 2 kilometres or more. As a result, the number of new permits for wind projects in Bavaria has plummeted.[48]

It will be interesting to observe the rate at which repowering takes place in the near future. In 2021 the first wind parks will drop out of the financing system established by the German government with the first EEG regulation in 2000. This opens up the potential for repowering at sites with great wind conditions, such as near coastal locations. Most of these sites will, however, be subject to the grid expansion area, where new capacity additions are limited according to EEG 2017.

To sum up: While there clearly is potential for higher cost efficiency, we also identified several regulatory hindrances to the cost optimal exploitation of wind power in Germany.

47 BWE (2016c)

48 BWE (2015)

6 Conclusions and Open Questions

Wind power costs are coming down, as indicated by the empirical evidence presented in this paper. This fundamental trend is projected to continue.

Large wind turbines are most cost efficient. Energy production is increased through greater rotor diameters. Higher hub heights allow to access steadier and stronger winds. And the costs for increasing turbine size grow at lower rates than the benefits. This is expected to be the major driver of future cost reductions. But what are the limits to onshore turbine growth? And will the limiting factor be of a technological nature, or a question of local political consent?

Turning to Germany: Good wind resources are key to low cost wind power. Under similar conditions, projects in Germany can be built with only slightly higher generation costs than the most cost efficient auction-winning projects throughout the world. The German government is hindering the exploitation of the best sites in Germany by restricting deployment within the grid expansion area. How many sites with excellent wind conditions are still available in Germany, and how many will be opened up for repowering in the near future? And how many sites are blocked from development, due to controversial distance and height restrictions?

The implications for the upcoming onshore wind auctions in Germany are not clear yet. Major potentials to improve cost efficiency are accelerating the trend to larger turbines and reducing land and maintenance costs, which are far higher than the international average. The cost of land in particular needs to become more transparent and warrants further investigation, since excessive rent-seeking seems to have become common practice.

Appendix

Expert Elicitation (Wiser et al. 2016)

The expert elicitation, which had 163 participants, was based on an online survey that was open between October and December 2015. The experts were asked to give high, median and low LCOE estimates for the years 2020, 2030 and 2050 based on a 2014 baseline. For the year 2030, opinions concerning five core input components were collected: total upfront capital expenditures, levelized annual operating expenditures, average annual energy output, project life and the cost of financing. Since the respondents were able to change the 2014 baseline (which was a subjective estimate) according to what they thought was a suitable value, our focus lies primarily on the relative changes in LCOE.

Among the group of respondents, 22 participants were identified as leading experts. The responses of this group were examined separately and compared to the ones of the entire expert group. This leading expert group turned out to be more optimistic than the larger group. They estimated an LCOE reduction of 27 per cent by 2030 and of 48 per cent by 2050 for the median scenario[49].

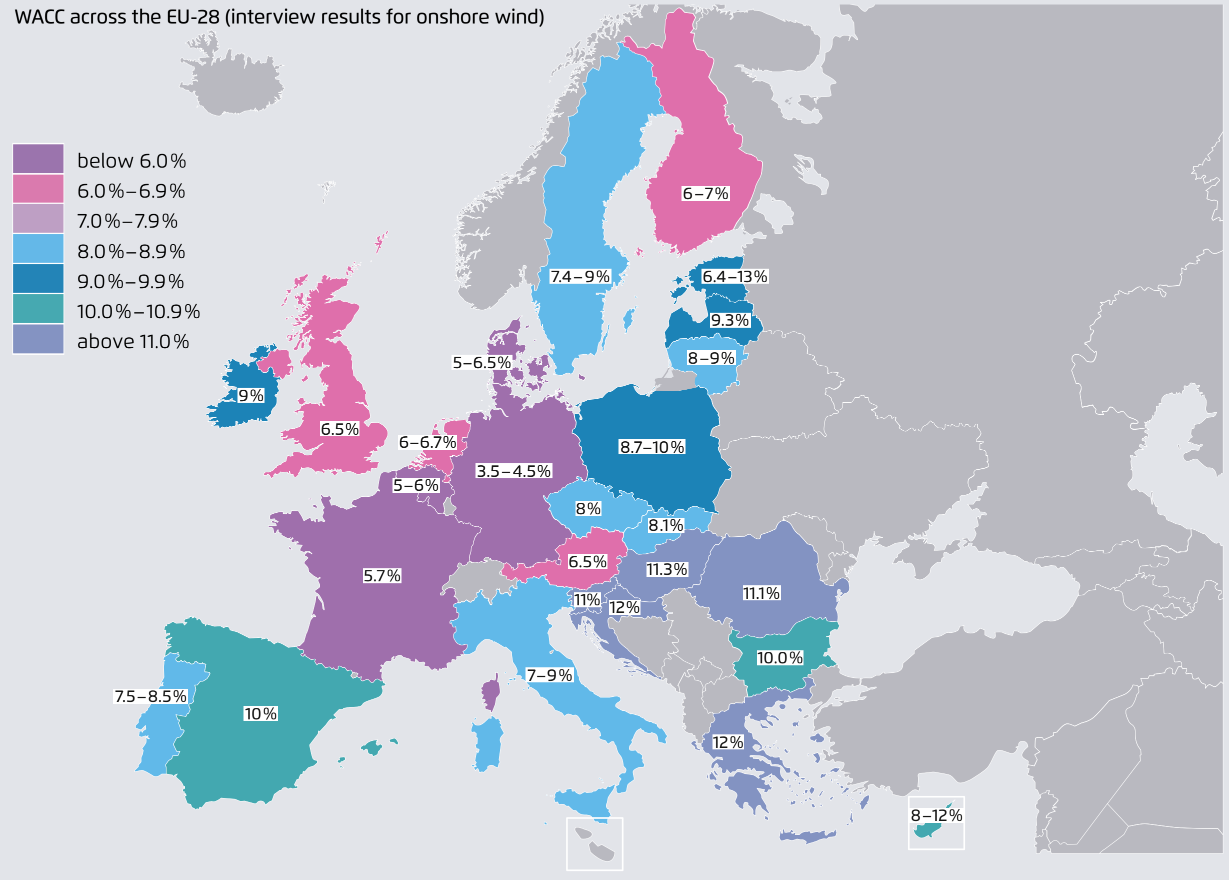
Capital Cost of Wind

Figure 6 shows the broad span of weighted average cost of capital for the EU-28 countries.

49 Wiser et al. (2016)

Weighted Average Cost of Capital (WACC) for onshore wind projects in Europe in 2014 — Figure 6

WACC across the EU-28 (interview results for onshore wind)



Agora Energiewende (2016) citing DIA-CORE (2016)

Technology Cost of Wind

The typical installed cost of an onshore wind power system ranges between 1,280 and 2,290 USD/kW (1,150–2,060 EUR/kW). The wind turbine itself is the most cost intensive part of an onshore wind project. It accounts for 64 per cent to 84 per cent of total installation costs in most wind projects.[50] A more detailed breakdown of capital costs from 2009 is shown in figure 7.

Factors and Limits in Wind Power Generation

The purpose of every wind turbine is to convert kinetic energy from wind air flow into rotational energy and the subsequent generation of electric power. The energy contained in the wind can be calculated as

$$P = \frac{1}{2}\dot{m}v^2 = \frac{1}{2}\rho A v^3$$

50 IRENA, IEA-ETSAP (2016)

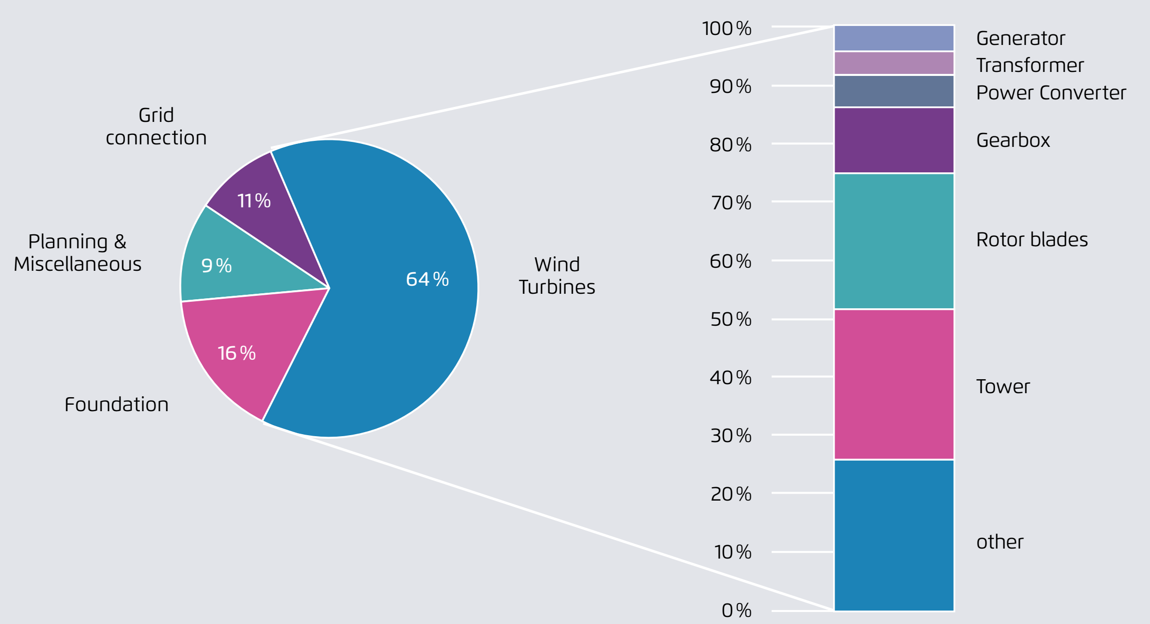
The yield is directly proportional to the cube of the wind velocity (v). Therefore, it increases by a factor of eight if wind speed is doubled. This highlights the importance of locations with high-quality wind resources as well as reliable models and tools to assess and predict wind conditions.[51]

Since power output is directly proportional to the rotor area (A), enlarging it is the second major factor in enhancing energy production. Increasing the rotor size has been an important part of the upscaling trend in recent years.

It is not possible to harvest all of the energy contained in the wind. The achievable yield with a specific wind turbine is dependent on its efficiency, whose theo-

51 WWEA (2014) provides an extensive overview of existing studies and wind maps regarding wind resources globally, as well as for nearly 40 different individual countries. Also see IRENA (2014) for the Global Atlas for Renewable Energy.

Capital cost breakdown for a typical onshore wind power system and turbine — Figure 7



adapted from Blanco (2009), cited in IRENA (2012, p. 18) retical limit is 59.3 per cent, according to Betz's law.[52] Actual efficiencies are around 45 per cent, due to aerodynamic, mechanical and electrical losses in the generation process.

Trends in Wind Turbine Production

General Trends

Wind turbines have been growing steadily in size since their market introduction, as larger turbines allow one to harvest more energy and access steadier wind flows. This trend is expected to last until insurmountable limits in turbine stability or production techniques are reached. UpWind (2011) predicts that a 20 MW turbine is feasible without significant problems, if some key innovations are integrated and developed.

With rotors and hub heights growing continuously, a rethink has taken place, leading producers to limit the nameplate capacity of their turbines through the use of smaller generators. As a result, the turbine "spills" some energy when winds are high, but is able to provide steadier output overall. This trend should not be interpreted as operators installing the same turbines with smaller generators, however. Rather, rotor size and hub height have increased at a faster rate than generator capacity, leading to a lower specific power. This can be seen in the US, where Class II or III turbines are installed in places where formerly Class I would have been used,[53] rendering more locations suitable for wind power generation.[54]

The use of larger turbines with a lower generator power per rotor area leads to more system friendly generation: When winds are high and new turbines harvest less than the optimum, energy prices are already low, since there is excess supply. The more important factor is generation output when winds are lower. During low wind periods, turbines with a low generator-to-rotor ratio will have a significantly higher output than traditional turbines with the same capacity, and therefore produce more electricity when prices are high.[55] This trend toward lower generator-to-rotor ratios also reduces the significance of forecasting errors, because of the greater range in which a steady supply of power is provided. Additionally, since extreme voltage peaks are drastically decreased, grid connection and expansion costs are reduced, and curtailment and redispatch measures become less common.

The extent to which onshore wind will benefit from the developments already made in the offshore industry remains unclear. Spillover effects could drastically increase the growth of turbines on land, since the technology is broadly in place offshore. In offshore applications, rotor diameters are as large as 180 meters,[56] while the largest onshore blades are currently at around 140 meters.[57]

Rotor and Hub

Status quo. The rotor consists of the blades and the hub, which connects the blades to the shaft. It is set in motion through the buoyancy principle by using airfoil similar to airplane wings. Blades are mainly fabricated from fibre composite materials, or wood in smaller applications. Recently, the use of carbon fibre has grown more and more prevalent.[58]

The pitch control system is located in the hub. It serves as a measure to regulate the rotational speed, and therefore the power output, by pivoting the blades. This changes the aerodynamic forces acting on the rotor and allows control over the rotational speed.

52 Betz (1920)

53 Wind classes rank sites according to the quality of their wind resource, from III (slow wind) to I (high wind). Turbines designated for Class II or III regimes usually have a greater rotor diameter and hub height than Class I turbines, since they have to compensate for lower wind speeds.

54 GWEC (2016)

55 Hirth et al. (2016)

56 Adwen AD 8-180

57 Enercon E141 EP4

58 Reinforced Plastics (2014)

Trends. In the coming years, the size of the rotor is very likely to increase further, allowing higher and steadier energy production in both low and high wind regimes. IRENA (2016) has developed forecasts for average diameter growth up to 2025 for leading wind energy countries. In Denmark rotor size is expected to grow from 104 to 125 m. The numbers for Germany (99 to 120 m) and the USA (99 to 119 m) are similar.

This growth in rotor diameter will be achieved in part through the improved prediction of load cases and rotor flexibility. KIC InnoEnergy (2014) stated that a load reduction of 30 per cent will be possible through the improved individual and collective pitching of the blades. Additionally, the introduction of smart rotors into the market might enable further reductions in material stress. By boosting flexibility (i.e. through piezoelectric elements or flaps), it will be possible to enhance the rotor's ability to react to different load cases. Load reductions will lead to greater rotor diameters, since they allow improved material utilization.

Furthermore, developments in the field of composite materials are expected advance material lifetimes. Today's models for fibre reinforced plastics are still insufficient to predict fatigue behaviour in multi-dimensional alternating loads. Further cost reductions are to be expected in the field of carbon fibre; McKinsey (2012), for example, expects the price of carbon fibre to drop between 45 and 66 per cent by 2030.

With increasing diameters, the production of one-piece blades will reach its limits, since the transportation process becomes too complicated. It can therefore be expected that the production of blades in two pieces that are later assembled on site will become the standard for the next generation of rotor blades. Two-piece production is already being done by Gamesa and Enercon, and we can expect other producers to adopt this principle. Taking things one step further, the first modular blades have reached the test phase. By assembling the blade from many smaller parts, new opportunities for the manufacturing and transport of very large blades will arise. Blade Dynamics has produced a test turbine according to this principle that was commissioned November 2015.[59] However, one cannot yet predict whether modular blades will become common in the market.

Nacelle and Drive Train

Status quo. There are two common concepts for the design of the transmission between the rotor and the generator. Doubly fed induction generators (DFIG) need a gearbox to translate the low rotational speed at the rotor shaft to a higher number of revolutions at the generator shaft, allowing the implementation of a small generator with a low number of poles. Gearbox parts, however, are prone to wear. Downtimes are often attributable to the need to replace bearings and gears.[60]

The direct drive (DD) concept makes use of ring generators, a synchronous generator with a high number of poles. This allows small angular speeds to be translated into an electric current with a higher frequency. Through eliminating the gearbox, the drive train becomes less susceptible to wear, more reliable and longer lasting. Furthermore, it enables more compact nacelle designs with less weight. For these reasons, DD is especially popular for offshore wind turbines, where high reliability, durability and low maintenance are desired. The downside of DD drive trains is their higher cost, which is partially attributable to permanent magnets, which conventionally require rare earth materials.

Trends. The general direction that manufacturers have chosen is leading to increasing reliability of the drive train. Some producers are switching their pro-

59 In 2015, GE purchased Blade Dynamics, releasing the following statement: "At GE, research and development is a key part of our long-term strategy. In our ongoing pursuit of cutting-edge wind technologies, we have followed recent advancements in composite manufacturing with great interest, and we believe modular blades could potentially become a transformational technology for the industry" (Windpower Monthly 2015).

60 EAWE (2016)

duction from DFIG to DD for offshore turbines. It is foreseeable that this will also lead to a change of philosophy in the onshore domain; Siemens, for example, has already switched to DD for onshore applications.[61] This development could speed up rapidly as soon as alternatives for rare earth materials are found, which IEA (2013) expects by 2025. Enercon has taken a different approach by using electromagnets.

Other innovations in the drive train design aim at improving the reliability of DFIG concepts by getting rid of the high-speed-stage of the gearbox. Through mid-speed-drive trains, stress can be reduced in gears and bearings, which are responsible for two thirds of all gearbox failures.[62]

Towers

Status quo. The most common tower for wind turbines has been the tubular steel tower, connected to the ground by a concrete foundation. However, tubular steel towers are only suitable for heights up to 100 meters.[63] This limitation has encouraged to new tower designs with heights up to 150 meters and more.

Trends. With onshore turbines surpassing 150 meters, manufacturers have already managed to overcome the technical limits set by tubular steel towers through the development of new design concepts. Conventional steel towers are restricted to a size of 100 meters for transportation and stability reasons. The most common way to deal with this problem is the switch to concrete. Hybrid solutions consisting of a lower concrete part and an upper steel section are possible, as are full concrete towers, which is today's standard for Enercon turbines. The circular segments can be produced on site, which avoids difficult transportation and is one of the main advantages over steel towers.[64]

There are other approaches for achieving high tower heights without using concrete. GE has developed the "Space Frame Tower", a lattice tower which allows faster installation than possible with a concrete tower. Seeking to preserve the advantages of tubular steel towers, Vestas has developed the "Large Diameter Steel Tower", which solves transportation issues by splitting the circular profiles and assembling the parts on site. Siemens, for its part, has met the need for increased heights by developing the "Bolted Steel Shell Tower", which makes use of a modular shell of bended steel plates.[65]

Operation and Maintenance

Status quo. There is still great deal of potential for cost reductions in the area of operation and maintenance (O&M). While significant advancements have been made in recent years, maintenance systems and methods for wind turbines have not reached the stage of maturity visible in other technological fields. This is attributable to the novelty of the technology combined with the remoteness of turbine sites, the particularities of unmanned operation, and the use of complex fibre composites in applications of unprecedented size. The optimization of systems and methods is still ongoing. Cost reduction potential is primarily evident in two areas: (1) the prevention and diagnosis of damage, and (2) O&M service costs. O&M costs are equal to 3 per cent of initial capital costs for smaller turbines, and are between 1 and 2 per cent for larger turbines. This difference relates to the fact that maintenance costs are nearly the same on a per turbine basis, and increase only slightly with turbine size.

Trends. It is expected that competition in the maintenance sector for wind turbines will continue to increase, which will further bring down prices. The maintenance contracts offered by the original manufacturers often only cover 3–5 years. Accordingly,

61 Siemens (2016b)

62 EAWE (2016)

63 de Vries (2014)

64 de Vries (2014)

65 de Vries (2014)

we can expect that operators will profit from falling prices or develop in-house expertise.[66]

One of the greatest challenges remains the prevention of unplanned maintenance. Wind turbines in Germany are subject to an average of 1–2 technical disturbances annually, and such disturbances usually trigger extended downtimes.[67] New developments in this area include the implementation of Structural Health Mechanisms, which are self-diagnosing instruments to monitor the rotor and tower, as well as Condition Management Systems, which control the bearings and gearbox. These measures can be effectively combined with full-time remote monitoring. An investigation by Enertrag (2016) found that such monitoring led to a 2 per cent increase in annual energy production.

An additional step for improving maintenance is the broad collection of O&M data. Standardized descriptions for components, damage cases and repair measures have been introduced and IEA is currently working on building an openly available database.[68] Through statistical analysis, more effective maintenance strategies will be developed. Such a database will also boost the potential for condition-based management, which has been trending in recent years.[69] The main objective of condition-based management is to replace parts when they are close to failure, when they have already failed, or at suitable times (e.g. when the wind is low).

Forecasting and Site Evaluation

The forecasting of wind and other weather conditions is essential for the establishment of wind as an effective and reliable power source. Such forecasting poses a major challenge, however, since it needs to cover time ranges from a few seconds to several decades, and has to account for local wind conditions and the effects of climate change on local wind resources.

On the one hand, forecasting is needed during site evaluation, when one seeks to predict wind conditions as precisely as possible for the next 20 years or more. Such forecasting is used to design the wind park in a way that will maximize returns and minimize costs. Accordingly, inaccurate forecasting can result in suboptimal wind park design, leading to higher costs and/or lower revenues.

On the other hand, forecasting is important for the operation of wind turbines. The precise prediction of wind conditions in coming days is important for trading electricity on the day-ahead market. Furthermore, short-term predictions of wind conditions are needed to improve operation of the turbine and plant, to manage critical load cases and to optimize the energy production.[70]

Status quo. Traditionally, anemometers are used to measure wind speeds when making siting decisions or operating a wind turbine. However, anemometers only allow measurement in the place where they are located. Furthermore, since they are normally installed downstream of a turbine, they only allow measurement of wind that has already passed the turbine.

Trends. The existing practice of measuring wind speeds with anemometers is being replaced by Light/Sound Detection and Ranging systems (LIDAR and SODAR). In the future, 3D LIDAR is expected to have a great impact on siting and operations, for it enables the measurement of various points in 3D space, with only one module. This enables the greatly improved characterization of the site-specific wind regime and the better design of wind farms. 3D LIDAR also minimizes wake effects (i.e. downstream turbulence caused by a turbine), thus boosting energy production.[71] GE introduced the "Digital Wind Farm" in 2015,

66 IRENA (2016)

67 BWE (2016b)

68 IEA Wind Task 33, BWE (2016b)

69 KIC InnoEnergy (2014)

70 EAWE (2016)

71 BWE (2016b), EAWE (2016)

an integrated digital-infrastructure concept for wind park development and operation that is expected to increase energy production by up to 20 per cent and to facilitate its integration in the power grid.[72] Integrated digital concepts will improve the anticipation of load cases and will help to proactively adjust to them. This will help to reduce stress on the blades and increase longevity.

Manufacturing

Status quo. The manufacturing of rotor blades is highly complex. Furthermore, there are no comparable production processes, because of the uniquely large dimensions of rotor blades. For stability reasons, most blades are still fabricated in one piece, which makes automatization difficult. As a result, blade production is still usually performed manually.

Trends. The automatization and standardization of blade production is of great interest to the industry, because it promises cost reductions and increased quality. Fraunhofer IWES is currently working on the BladeMaker project, which aims to reduce manufacturing costs by 10 per cent through the automatization of certain production steps.[73]

Further cost reductions seem possible if modular blades become successful on the market. This would allow the use of production facilities normally used for manufacturing plane, boat or automotive components, thus avoiding the need for highly specialized factories, as is the case today.[74]

72 GE (2015)

73 IWES (2016)

74 Clean Technica (2015)

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Endbericht einer Studie von der Prognos AG und dem Institut für Elektrische Anlagen und Energiewirtschaft (IEAW)

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Agora Energiewende develops evidence-based and politically viable strategies for ensuring the success of the clean energy transition in Germany, Europe and the rest of the world. As a think tank and policy laboratory we aim to share knowledge with stakeholders in the worlds of politics, business and academia while enabling a productive exchange of ideas. Our scientifically rigorous research highlights practical policy solutions while eschewing an ideological agenda. As a non-profit foundation primarily financed through philanthropic donations, we are not beholden to narrow corporate or political interests, but rather to our commitment to confronting climate change.

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