20 Wind Turbines onshore

Contact information:
Danish Energy Agency: Thøger Kiørboe, TKI@ens.dk
Author: Mads V. Sørensen /Henrik Sundgård Petersen / Per Nielsen (EMD)

Publication date
August 2016

Amendments after publication date

Date	Ref.	Description
May 19	20 Wind turbines onshore	Financial and technical data updated in data sheets

Note to Amendment May 2019:
A significant reduction in turbine costs has been observed in the past years. Also, a faster development in rotor size than expected in the 2016 version has been observed. Larger generators, larger hub heights and larger rotors have all contributed to increase the electricity generation from wind turbines. However, the most radical change is related to service costs. These are reduced by approximately 50% since the 2016 version of this chapter. At the same time electricity prices has increased in recent year which makes onshore wind turbines close to independent of subsidies. This is illustrated by the results of the first Danish auction (finalized in late 2018) where the average feed-in premium was as low as 2.27 øre/kWh (both onshore wind and solar PV). Also the first subsidy-free onshore project was announced in March 2019.

Since the 2016 version of this chapter additional cost components has been included in the data sheets. These include land purchase, compensations to neighbours, purchase of neighbour settlements and purchase of old turbines.

Besides the cost reductions, also technical improvements have been seen. More advanced control of the turbines continues to develop. An example is “power boost”, where the turbine will run above rated power when the conditions allow (like generator temperature). This means added production at the part of the power curve where the turbine starts to reduce output. Also, high wind “ride through” is seen, where the turbine does not stop at 25 m/s but continue to operate. This does not give much extra production but can be a huge advantage for the grid. Shutdown of 5 GW wind power within few hours when a hurricane arrive, is a huge challenge for grid operation. A new “control” is in test now, where a wind farm is controlled in a way that maximizes the output for the total wind farm, by detailed control of each turbine to minimize wake losses and at the same time reduce loads.

The new control strategies, however, do not add significant amounts of annual production, probably only a few percent extra.

Qualitative description

Brief technology description

The typical large onshore wind turbine being installed today is a horizontal-axis, three bladed, upwind, grid connected turbine using active pitch, variable speed and yaw control to optimize generation at varying wind speeds.

Wind turbines work by capturing the kinetic energy in the wind with the rotor blades and transferring it to the drive shaft. The drive shaft is connected either to a speed-increasing gearbox coupled with a medium- or high-speed generator, or to a low-speed, direct-drive generator. The generator converts the rotational energy of the shaft into electrical energy. In modern wind turbines, the pitch of the rotor blades is controlled to maximize power production at low wind speeds, and to maintain a constant power output and limit the mechanical stress and loads on the turbine at high wind speeds. A general description of the turbine technology and electrical system, using a geared turbine as an example, can be seen in figure 1.

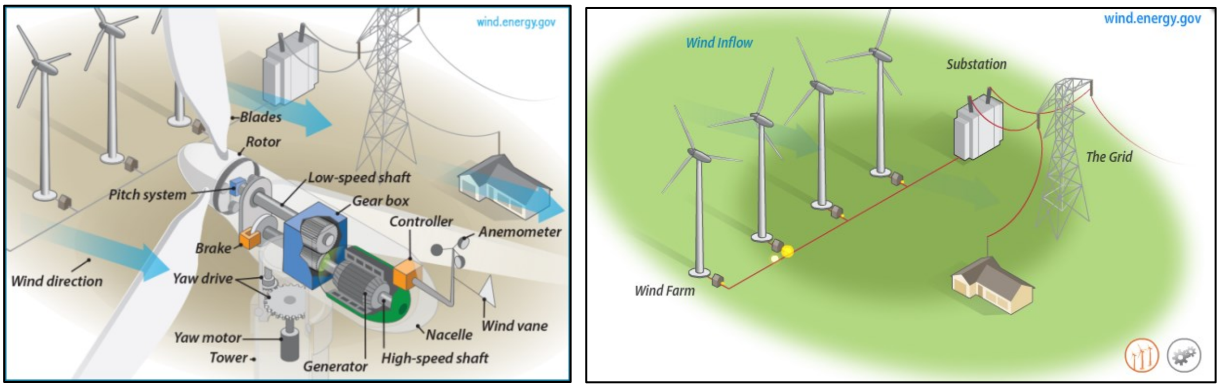

Figure 2 General turbine technology and electrical system.

Wind turbines are designed to operate within a wind speed range which is bounded by a low “cut-in” wind speed and a high “cut-out” wind speed. When the wind speed is below the cut-in speed the energy in the wind is too low to be utilized. When the wind reaches the cut-in speed, the turbine begins to operate and produce electricity. As the wind speed increases, the power output of the turbine increases, and at a certain wind speed the turbine reaches its rated power. At higher wind speeds, the blade pitch is controlled to maintain the rated power output. When the wind speed reaches the cut-out speed, the turbine is shut down or operated in a reduced power mode to prevent mechanical damage.

Onshore wind turbines can be installed as single turbines, clusters or in larger wind farms.

Commercial wind turbines are operated unattended and are monitored and controlled by a supervisory control and data acquisition (SCADA) system.

Input

Input is wind.

Cut-in wind speed: 3 – 4 m/s.

Rated power generation wind speed: 10-12 m/s, depending on the specific power (defined as the ratio of the rated power to the swept rotor area).

Cut-out or transition to reduced power operation at wind speed: 25 m/s.

In the future, it is expected that manufacturers will apply a soft cut-out for high wind speeds (indicated with dashed red curve in figure 2) resulting in a final cut-out wind speed around 30 m/s.

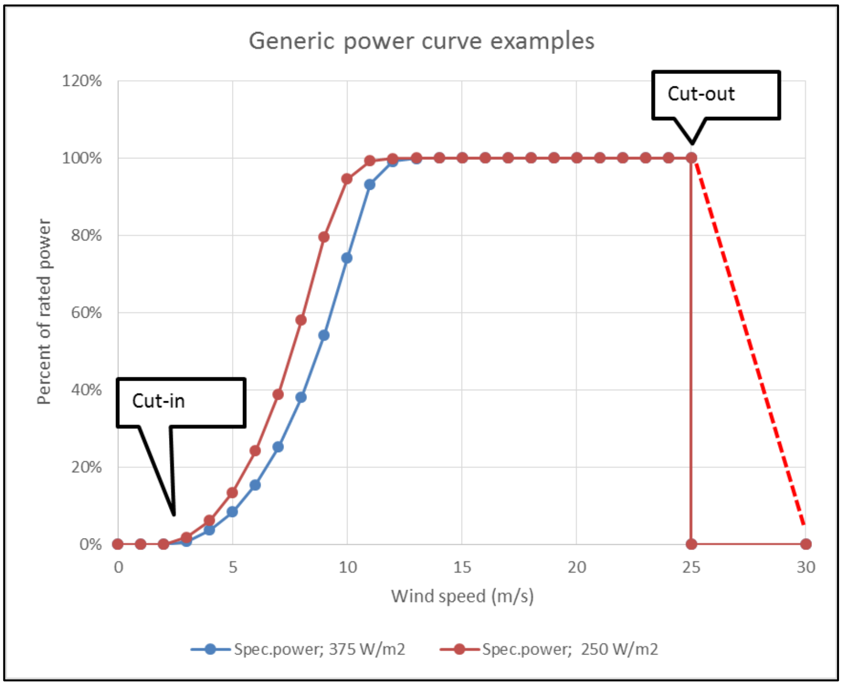

Figure 3 Turbine power curves (Information's from expert workshop held by DEA 27-4-2015). Specific power values refer to e.g. 3 MW with 124m rotor diameter (250 W/m2) and 3 MW with 101 m rotor diameter (375 W/m2)

The power in the wind is given by the formula $P = ½*rho*A*u^3$, where rho is the air density, A the swept area and u the wind speed. To calculate the net power output from a wind turbine, the result must be multiplied by C_p (Coefficient of power). C_p varies with wind speed and has a maximum of around 45%, which is typically reached at ~8 m/s, depending on the specific power.

Output

The output is electricity.

Typical modern onshore turbines located in Denmark have capacity factors in the range of 35%, corresponding to 3100 annual full load hours. Typical duration curves are presented in Figure 4.

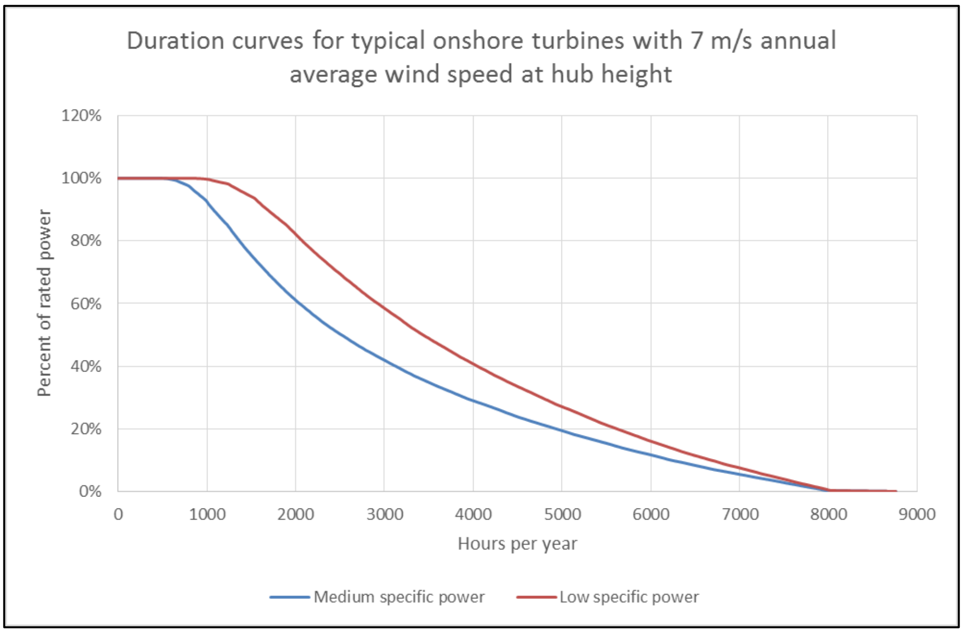

Figure 4 Duration curve for typical modern onshore wind turbines (> 2 MW) located in Denmark (DTU International Energy Report - Wind Energy, 2014). The two curves are based on the V117 3.3 MW (307 W/m2) and V126 3.3 MW (265 W/m2) wind turbines.

The annual energy output of a wind turbine is strongly dependent on the average wind speed at the turbine location. The average wind speed depends on the geographical location (with North-western Jutland being the windiest part of Denmark), the hub height, and the surface roughness. Hills and mountains also affect the wind flow, but as Denmark is very flat, the local wind conditions are normally dominated by the surface roughness. Also, local obstacles like forest and for small turbines buildings and hedges reduce the wind speed like wakes from neighbour turbines reduces.

The surface roughness is normally classified according to the following table:

Roughness class	Roughness Length (m)[9]	Description
0	0.0002	Water
1	0.03	Open farmland
2	0.1	Partly open farmland with some settlements and trees
3	0.4	Forest, cities, farmland with many windbreaks

Table 1: Description of classification of surface roughness

[9] The roughness length is the height above ground level, where average wind speed is 0. The wind speed variation with height is governed by the roughness length.

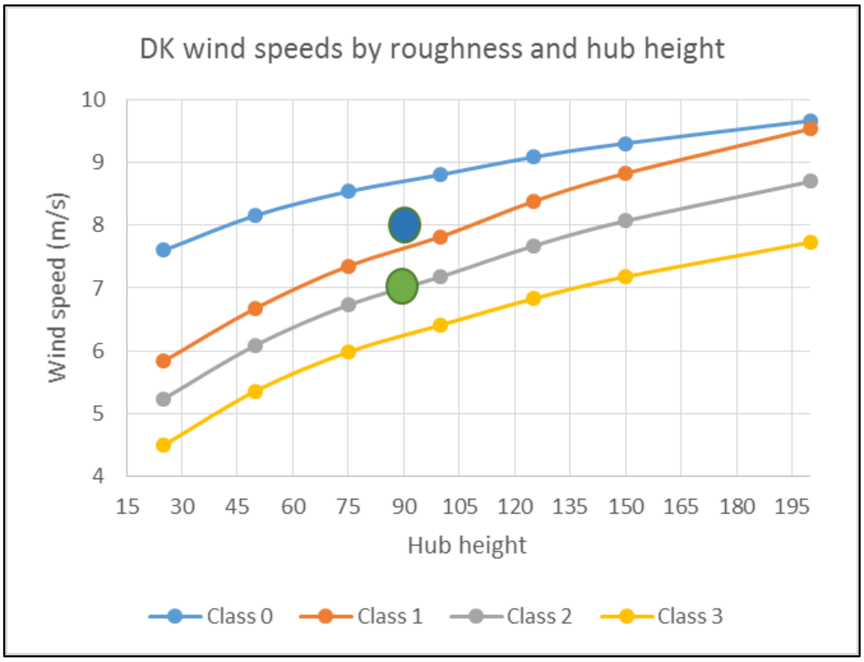

Figure 5 Annual average wind speeds as a function of hub height and roughness class for flat terrain. The green dot represents a typical modern inland site; the blue dot represents a typical coastal site. The typical hub height is 90 m.

Figure 5 shows the average wind speeds by hub height and roughness class for flat terrain. Onshore wind turbines installed in Denmark today typically have a hub height of 85-90 m. On a typical inland site the average wind speed is around 7 m/s, whereas on a typical coastal site the average wind speed is around 8 m/s. An increase in the average wind speed from 7 to 8 m/s results in a roughly 25% increase in annual energy production.

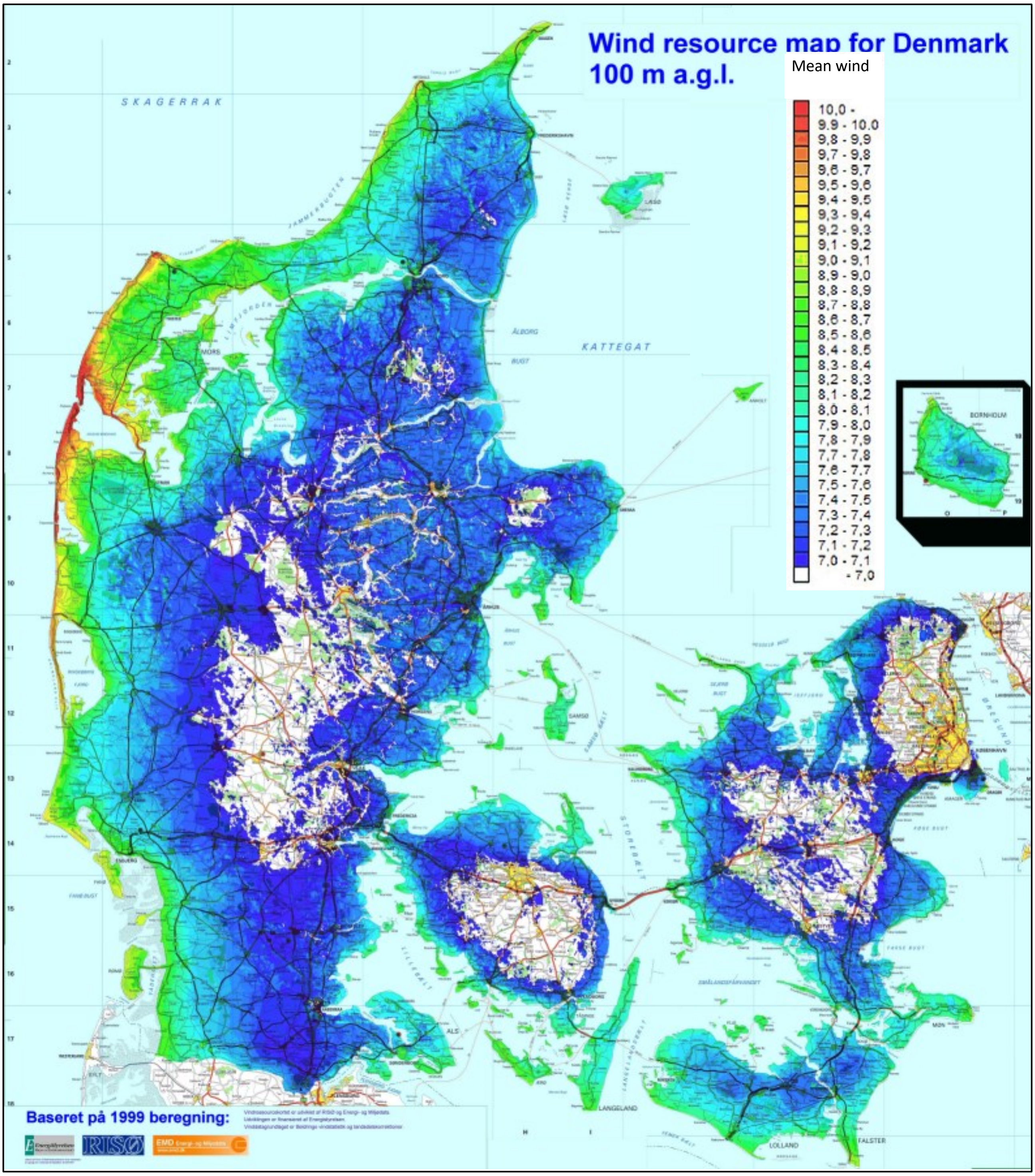

Figure 6 Wind resource map for Denmark in 200 m resolution, 100 m above terrain .

The wind resource map for Denmark (Figure 6) shows the regional differences. As seen, the regions close to the sea in dominating wind directions (west-southwest) that have the highest wind resource. This is a result of the low surface roughness in the upwind direction. The white areas have average wind speeds below 7 m/s at 100 m height above terrain.

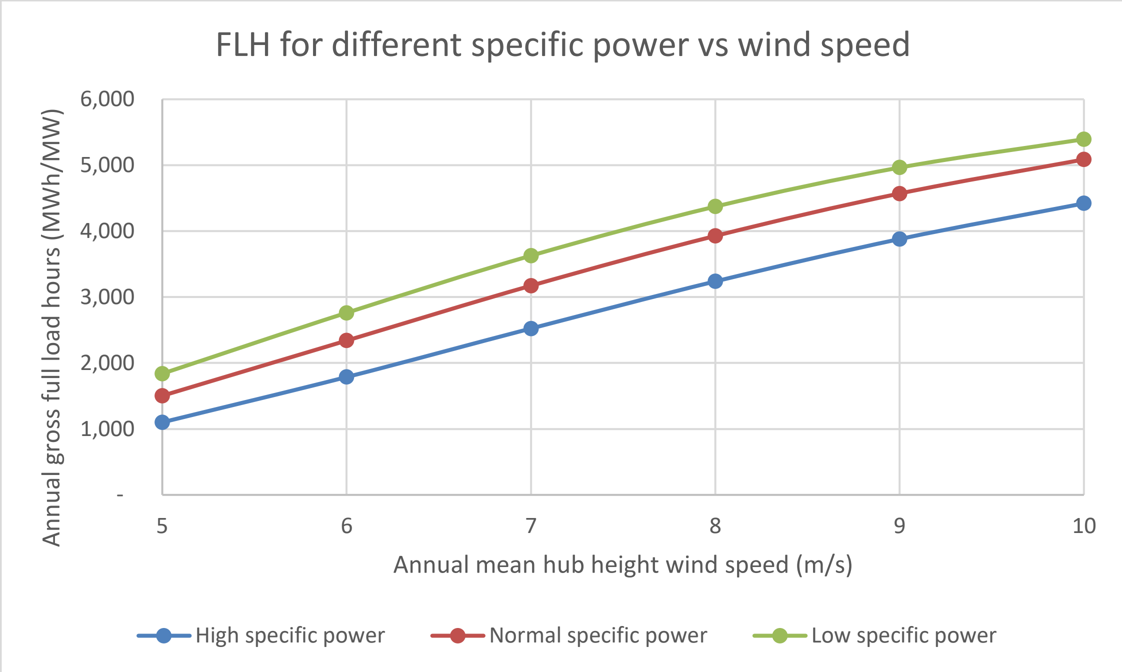

Figure 7 Annual full load hours as a function of mean wind speed at hub height. The examples in the figure are 3 MW with 90m rotor diameter, specific powers are 472 W/m2 called "high specific power" and 3.3 MW turbines with 112 m and 126 m rotor diameters, specific powers are 335 W/m² called "medium specific power" and 265 W/m² called "low specific power".

Figure 7 illustrates the importance of the annual mean wind speed as well as the specific power for the annual energy production (AEP). It is seen that the increase in AEP is almost linear with mean wind speed in the range from 6m/s to 9 m/s. Future turbines are expected to have even lower specific power than the "low" example in above figure.

Typical capacities and development statistics

Onshore wind turbines can be categorized according to nameplate capacity. At the present time new installations are in the range of 2 to 6 MW. Another category is domestic wind turbines which is micro and small wind turbine in the range of 1 -25 kW, see separate paragraph on domestic turbines.

Two primary design parameters define the overall production capacity of a wind turbine. At lower wind speeds, the electricity production is a function of the swept area of the turbine rotor. At higher wind speeds, the power rating of the generator defines the power output. The interrelationship between the mechanical and electrical characteristics and their costs determines the optimal turbine design for a given site.

The size of wind turbines in Denmark has increased steadily over the years. Larger generators, larger hub heights and larger rotors have all contributed to increase the electricity generation from wind turbines. Lower specific capacity (increasing the size of the rotor area more than proportionally to the increase in generator rating) improves the capacity factor (energy production per generator capacity), since power output at wind speeds below rated power is directly proportional to the swept area of the rotor. Furthermore, the larger hub heights of larger turbines provide higher wind resources in general.

The average rated power of new onshore wind turbines in Denmark has increased by a factor of three since year 2000 (Figure 8 below). Although project developers consider larger turbines to be the most attractive, the increase in rated power is not constant, partly because some older projects with smaller turbines have been expanded with more (small) turbines, and partly because some projects are established with smaller turbines than the "optimal" size due to lack of space.

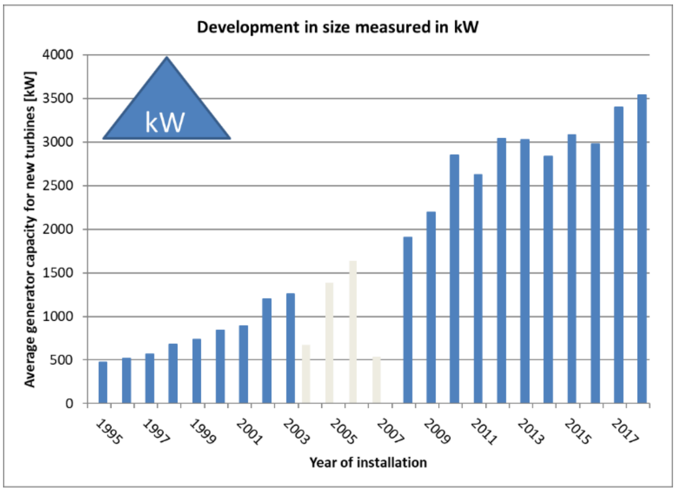

Figure 8 Average generator capacity for new turbines (rated power > 25 kW) [3]

In the same period the rotor diameters and hub heights have also increased as illustrated in figure 8 and 9.

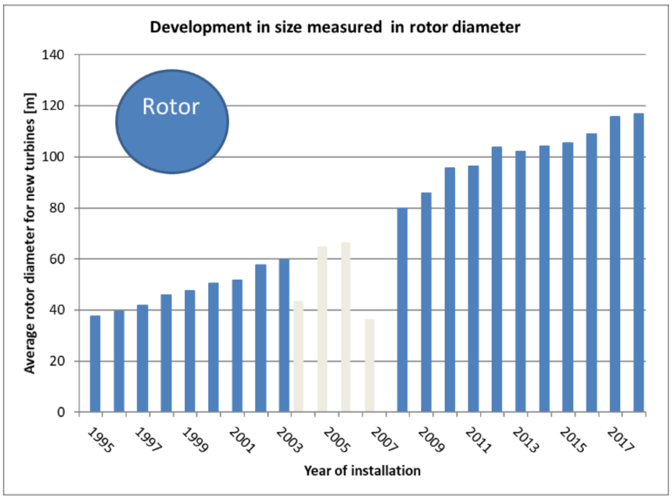

Figure 9 Average rotor diameter for new turbines (rated power > 25 kW) [3]

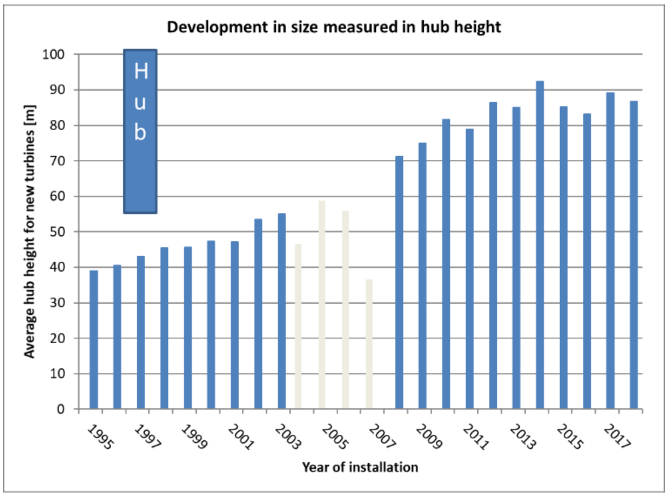

Figure 10 Average hub height for new turbines (rated power > 25 kW) [3]

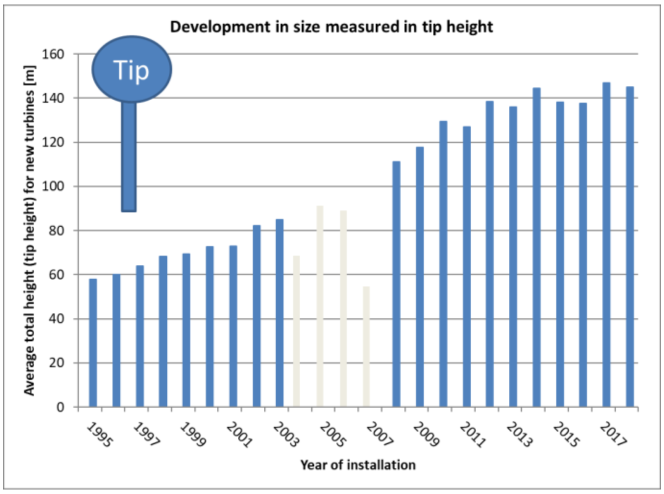

Figure 11 Average tip height for new turbines (rated power > 25 kW) [3]

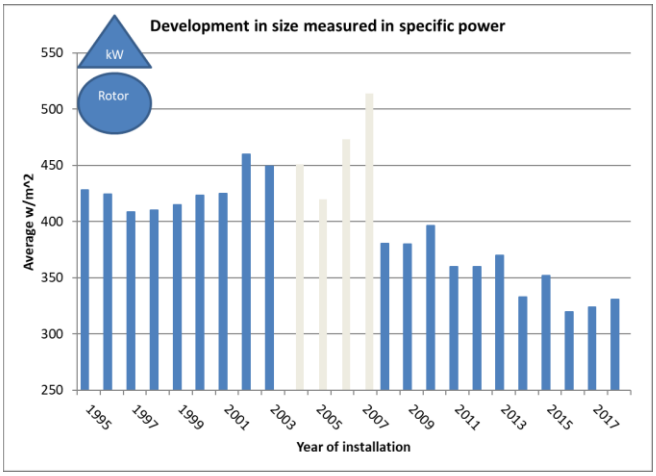

Figure 12 Average specific power for new turbines (rated power > 25 kW) [3]

The specific power has decreased for turbines installed in Denmark over the last 10 years. Formerly, turbines often had specific power values on the order of 400-450 W/m2. Since 2010 the average specific power has generally been less than 375 W/m2. In combination with improvements in turbine efficiency and an increase in average hub heights, this has resulted in increasing capacity factors. On average, capacity factors for Danish onshore turbines installed before 2000 were below 25% (corresponding to 2200 full load hours), while the average capacity factors for Danish onshore turbines installed after 2010 are typically in the order of 30-35% (corresponding to 2600-3100 full load hours). The trend towards larger rotors and lower specific power is global.

Due to current planning, environmental and civil aviation regulations wind turbines to be installed onshore in Denmark are generally limited to a maximum height of 150 m from the ground to the highest point i.e. rotor tip. In 2018 the average total height (tip height) was 145 m [4]. However, exemptions from the 150 m limit are granted for test sites. Elsewhere in Europe there is a strong trend towards approval of maximum heights above 150 m. Removal of the 150 m limitation is currently being processed and is expected to be removed from the Danish regulations in 2019.

Regulation ability and power system services

Electricity from wind turbines is highly variable because it depends on the actual wind resource available. Therefore, the regulation capability depends on the weather situation. In periods with calm winds (wind speed less than 4-6 m/s) wind turbines cannot offer regulation, with the possible exception of voltage regulation.

With sufficient wind resource available (wind speed higher than 4-6 m/s and lower than 25-30 m/s) wind turbines can always provide down regulation, and in many cases also up regulation, provided the turbine is running in power-curtailed mode (i.e. with an output which is deliberately set below the possible power based on the available wind).

In general, a wind turbine will run at maximum power according to the power curve (c.f. figure 10) and up regulation is only possible if the turbine is operated at a power level below the power actually available. This mode of operation is technically possible and, in many countries, turbines are required to have this feature. However, it is rarely used, since the system operator will typically be required to compensate the owner for the reduced revenue [5].

Wind turbine generation can be regulated down quickly, and this feature is regularly used for grid balancing. The start-up time from no production to full operation depends on the wind resource available.

New types of wind turbines (DFIG and converter based) also have the ability to provide supplementary ancillary services to the grid such as reactive power control, spinning reserve, inertial response, etc. However, these supplementary ancillary services from wind turbines are seldom utilized in Denmark, due to a lack of economic incentives. Older types of wind turbines typically deployed in Denmark before 2008 consume reactive power and can have a negative influence on voltage stability.

Advantages/disadvantages

Advantages:

- No emissions to air from operation
- No emission of greenhouse gasses from operation
- Stable and predictable costs due to low operating costs and no fuel costs
- Modular technology allows for capacity to be expanded according to demand avoiding overbuilds and stranded costs
- Short lead time compared to most alternative technologies

Disadvantages:

- High capital investment costs
- Variable energy resource
- Moderate contribution to capacity compared to thermal power plants
- Need for regulating power
- Visual impact and noise

Environment

Wind energy is a clean energy source. The main environmental concerns are visual impact, flickering from rapid shifts between shadow and light when turbine is between sun and settlement, noise and the risk of bat or bird-collisions.

The visual impact of wind turbines is an issue that creates some controversy, especially since onshore wind turbines have become larger.

Flickering is generally managed through a combination of prediction tools and turbine control. Turbines may in some cases need to be shut down for brief periods when flickering effect could occur at neighbouring residences.

Noise is generally dealt with in the planning phase. Allowable sound emission levels are calculated on the basis of allowable sound pressure levels at neighbours. In some cases, it is necessary to operate turbines at reduced rotational speed and/or less aggressive pitch setting in order to meet the noise requirements. Noise reduced operation may cause a reduction in annual energy production of 5-10%. Despite meeting the required noise emission levels turbines sometimes give rise to noise complaints from neighbours. In 2013 it was decided to investigate in detail how wind turbines and especially noise from wind turbines influence human health. The report concludes[10] that:

- No conclusive evidence was found of a correlation between short-term and long-term exposure to wind turbine noise and the occurrence of blood clots in the heart and stroke.

- The results of the study do not support a link between long-term exposure to wind turbine noise and newly emerging diabetes or between exposure to wind turbine noise during pregnancy and negative birth defects.

- For first-time redemption of prescriptions for sleep medication and antidepressant medicine, the researchers found a connection with high levels of outdoor wind turbine noise among the elderly over the age of 65 and weak indications of similar findings for first-time intake of prescriptions for medicines for the treatment of high blood pressure.

- The study generally includes few illnesses / pregnancies among the groups exposed to the highest noise levels, which is why the researchers demand that the results be reproduced by other researchers

A recent Canadian literature study concludes that wind turbines might cause annoyance at the neighbours, but no causal relation could be established between noise from wind turbines and the neighbour's health [7].

The risk of bird collisions has been of concern in Denmark due to the proximity of wind turbines to bird migration routes. In general, it turns out that birds are able to navigate around turbines, and studies report low overall bird mortality but with some regional variations [8].

The environmental impact from the manufacturing of wind turbines is moderate and is in line with the impact of other normal industrial production. The mining and refinement of rare earth metals used in permanent magnets is an area of concern [2, 9, 10].

The energy payback time of an onshore wind turbine is in several studies calculated to be in the order of 3-9 months [11, 12].

Life-cycle assessment (LCA) studies of wind farms have concluded that environmental impacts come from three main sources:

- bulk waste from the tower and foundations, even though a high percentage of the steel is recycled
- hazardous waste from components in the nacelle
- greenhouse gases (e.g. $CO2$ from steel manufacturing and solvents from surface coatings)

Research and development perspectives

R&D potential: [2, 13]

- Reduced investment costs resulting from improved design methods and load reduction technologies

10 https://mst.dk/service/nyheder/nyhedsarkiv/2019/mar/undersoegelse-om-helbredseffekter-af-vindmoellestoej-er-afsluttet/

- More efficient methods to determine wind resources, incl. external design conditions, e.g. normal and extreme wind conditions
- Improved aerodynamic performance
- Reduced operational and maintenance costs resulting from improvements in wind turbine component reliability
- Development in ancillary services and interactions with the energy systems
- Improved tools for wind power forecasting and participation in balancing and intraday markets
- Improved power quality. Rapid change of power in time can be a challenge for the grid
- Noise reduction. New technology can save the losses by noise reduced mode and possible utilize good sites better, where the noise set the limit of number of turbines
- Public acceptance
- Repowering strategies, like when it is feasible to repower for society and for investors – subsidy schemes must support optimal solutions
- Storage can improve value of wind power much, but is expensive at present

Examples of best available technology

Presently only Siemens and Vestas have commercially approved turbines suitable for Danish onshore projects. The wind turbines offered have rated power in the 2–5 MW range and rotor diameters of 80-150 m. Hub heights are typically in the range of 80-100 m within the current limit of 150 meter height. With the expected removal of the 150 meter limit, taller turbines with larger rotors will become possible in Denmark.

Prediction of performance and cost

Cost breakdown of total capital costs for onshore wind turbines

The 2020 estimate of capital costs is based on cost data for 12 onshore wind projects installed in 2017 and 2018.

The capital costs of onshore wind power projects are dominated by the cost of the wind turbine itself. The cost of grid connection has historically been covered by the Transmission System Operator (TSO) or Distribution System Operator (DSO) depending on the connection point. These costs do not appear in the cost breakdown from the 12 projects included in the analysis. Grid connections are generally 3 to 7 % of total investment costs.

Included in the cost breakdown are the following supplementary project costs (not included in previous version of the catalogue):

- Cost of land
- Compensation for loss of value for nearby settlements (Værditabsordningen)
- Purchase of existing turbines to be dismantled at site or nearby
- Purchase of nearby settlements to free space for the project

These costs are highly variable from project to project and can vary from 0% to round 25% of the total investment, depending on the local situation.

The cost breakdown based on 12 projects installed 2017-18 are shown below.

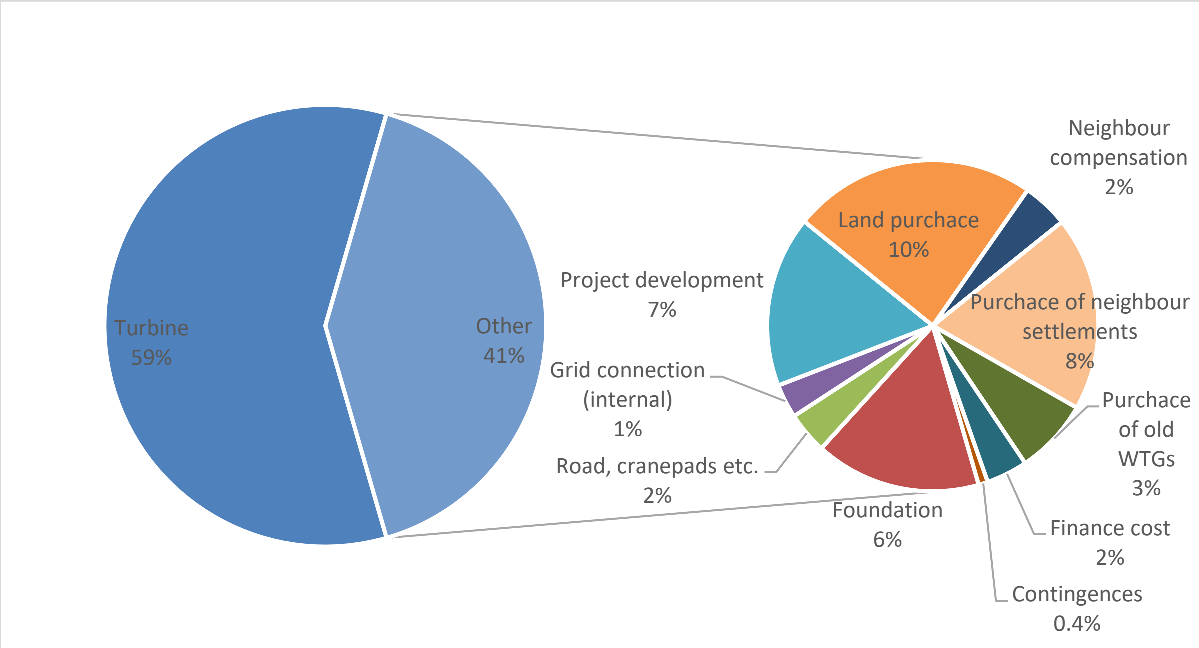

Figure 13 The cost breakdown including land costs etc. from "køberetsordning" 2017-18 projects.

The costs of purchase of neighbour settlements, old WTGs and neighbour compensation might increase in future, while there is a trend towards larger projects that require more space and thereby added costs for the mentioned issues.

External grid costs are not included in the cost breakdown, while this cost so far has been covered by TSO or DSO as mentioned above. For future projects these shall be covered by the project. The costs are roughly estimated to 5% of all other costs. These costs can vary much by project location. In addition there will be expected added future cost for a replacement of the "grøn ordning", where roughly 10.000 €/MW could be obtained by municipalities for local initiatives with purpose of gain of acceptance.

There are four major components in operation and maintenance costs for wind turbines in Denmark: Service agreement, insurance, land rent/administration and repairs not covered by service agreement. Each cost component accounts historically roughly for 25% of Operating and Maintenance (O&M) costs over the lifetime of a wind turbine [4]. For more recent projects the trend is that the service agreement cover more and insurance and repair cost will represent a lower percentage.

A major part of the most recent onshore wind turbines is delivered with long term service contracts (more than 10-15 years) provided by the turbine manufacturers and a large part of the service/maintenance costs is known upfront. However, it is difficult to estimate the costs for repairs not covered by the service agreement, and even with long-term service agreements unforeseen cost may occur [15].

A study based on data for 2009 reports the expected lifetime costs for O&M for wind turbines installed in Denmark to be approximately €12/MWh (2015 prices) [4]. This is in accordance with the latest experience from the Danish Wind Turbine Owners association, which estimates a lifetime O&M-cost of 11 €/MWh (2015 prices) [15]. During 2018 an increased competition on service agreement is seen, where costs down to 50% of the years before are seen.

Cost and production dependence of hub height and specific power

To identify main drivers for future technology a deeper look is taken on how the production changes relative to the cost of the turbines by different parameter variations.

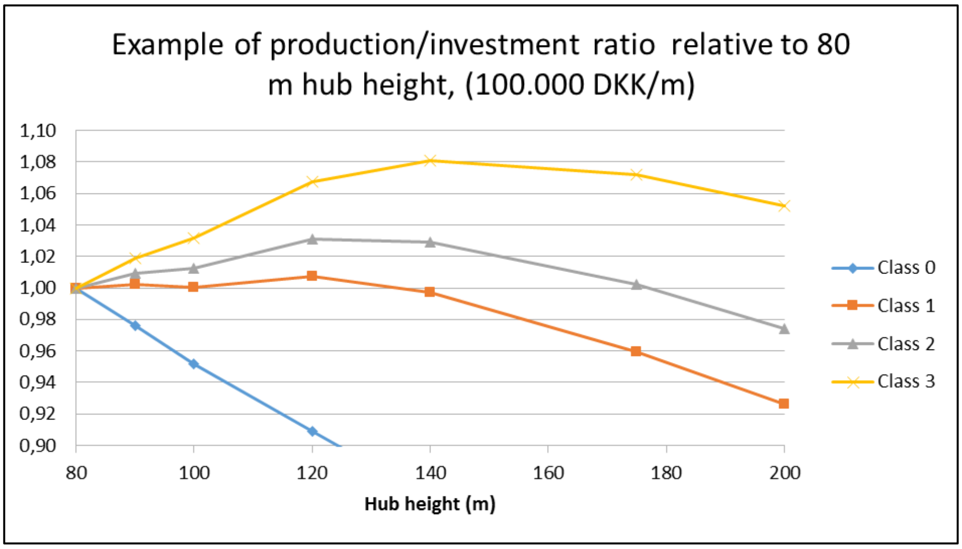

Figure 14 The production increase relative to the investment cost based on current available Vestas turbines. By increasing height, costs are extrapolated using DKK 100.000 per m hub height increase; the rotor area is kept constant.

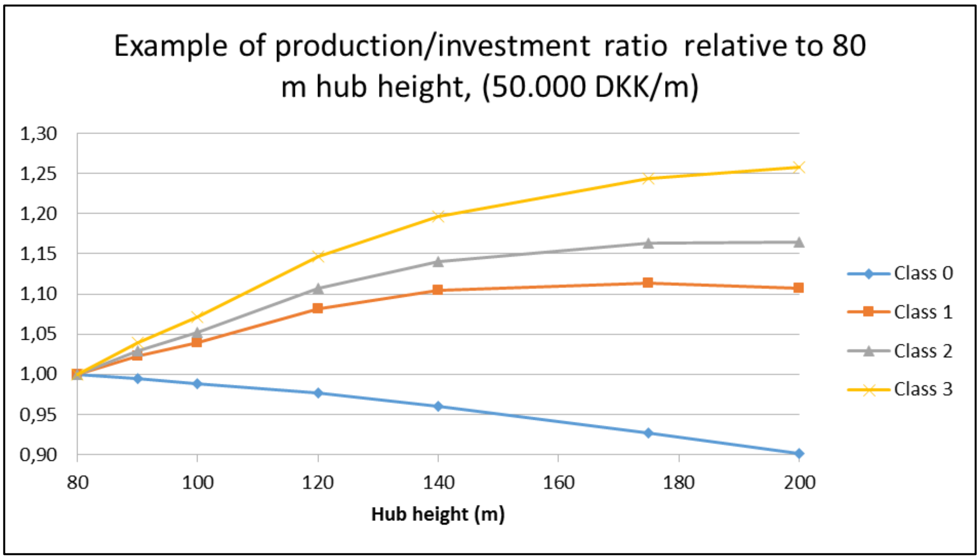

Figure 15 Similar, the production increase relative to the investment cost based on current available Vestas turbines, for increasing height, where costs are extrapolated using DKK 50.000 per m hub height increase, the rotor area is kept constant.

Figure 14 and Figure 15 demonstrate that except for in the offshore roughness class 0 hub heights above today’s standard would lead to improved cost efficiency. In countries like Germany and Sweden, the improvements are generally at the higher end due to a higher average roughness class, and in the recent years 140m hub height are becoming common in commercial projects.

While the assumed cost increase of DKK 50-100.000 per meter hub height increase is within the range seen of present technologies, many other factors contribute to the cost increase with height, such as the specific tower technology, the project location relative to manufacturing, and the available cranes. Consequently, the cost increase will not be linear with height (as assumed in the figures), and the figures should be taken as a general illustration of the potential cost reductions by increased hub heights.

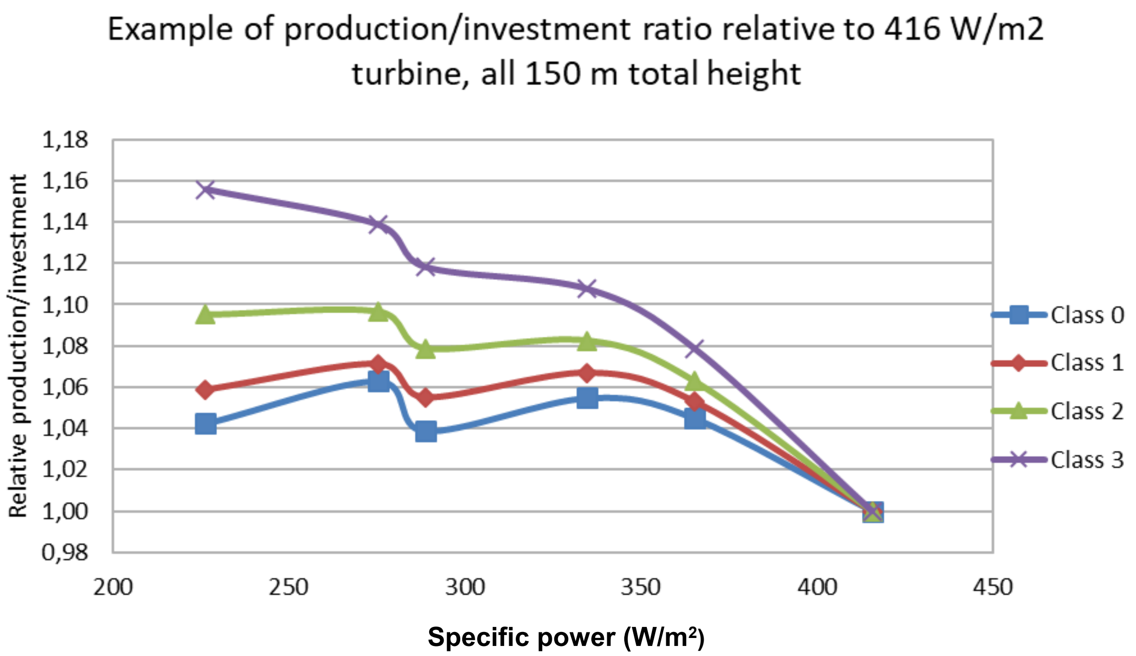

Figure 16 The production relative to the investment cost based on current available Vestas turbines for different rotor areas, generator size is 3.6 - 4 MW for all (= different specific power).

Figure 16 illustrates the potential benefits from reduction of the specific power. Turbine models with a specific power of less than 250 W/m^2 have up to 15% improvement in energy production per cost when comparing to the present model with highest specific power. If the improvement due to hub height increase would be included, even higher improvements would be seen.

To some extent the average capacity factors of onshore turbines installed since 2010 are affected by noise reduced operation due to noise regulations. Typically, noise reduced operation results in around 5% lower annual production than if non-noise reduced operation was possible. While the noise reduced mode will typically reduce around 5% with the Danish regulations, some higher reductions are seen in other countries.

Prediction of cost in 2015

The investment cost of wind turbines is expressed as investment per installed MW. This should however not stand alone when assessing the cost of the production of electricity from wind turbines. As mentioned before, the increase in hub height and rotor size of the turbine incurs additional investment costs per MW, but also increases the production per MW.

The development in the cost of wind turbines per installed MW and the numbers of full load hours are shown in Figure 17. Costs increased between 2002 and 2008. This was due to increased size and technical complexity of wind turbines and increased costs of steel, other raw materials and labour during this period, increased mark-ups by wind turbine manufacturers, and the effects of supply chain shortages for wind turbines and key components.

At the same time the electricity production per MW (annual full load hours) increased due to increases in the size and other technological improvements.

Figure 15 illustrates how the energy production (annual full load hours) and the investment cost has developed since 1995. In Figure 17 it is seen that in the recent years (2008-2014) the increase in energy production has been higher than the increase in investment costs.

The year-by-year variations are mainly a reflection of the sensitivity to the wind resource of actual project, rather than a year-to-year change in the technology used. Turbines installed during the period 2010-12 have the highest number of full load hours. This is probably most related to the fact that the majority of the turbines installed during this period are located in western Jutland which has the best wind resources in Denmark.

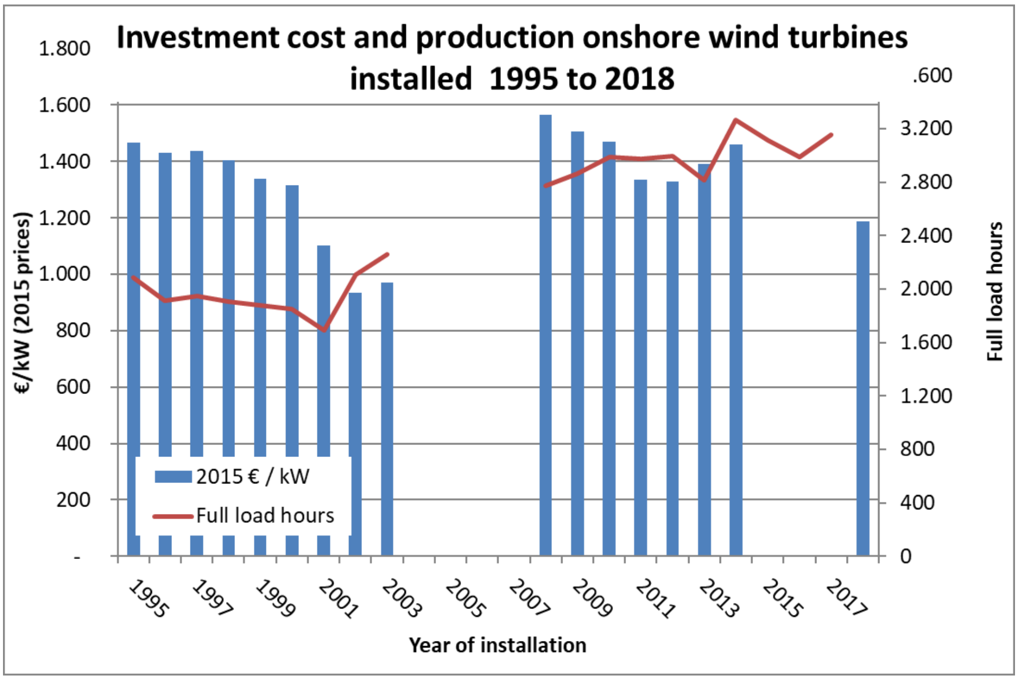

Figure 17 Development in investment cost (2015 price level) and average production (full load hours) for onshore turbines > 25 kW by installation year based on 2018 production [3, 16, 2]

Data from projects, which has been decided in 2013 and 2014 showed that the average investments costs for these projects are approximately 1450 k€/MW [14]. The costs of the installed projects 2017-18 was round 1200, all-inclusive land rent, neighbour compensations etc. This show a cost reduction of round 20% recent 4 years. The figure above does not include data for 2015-17, since the data basis not is detailed enough to give year by year data in this period.

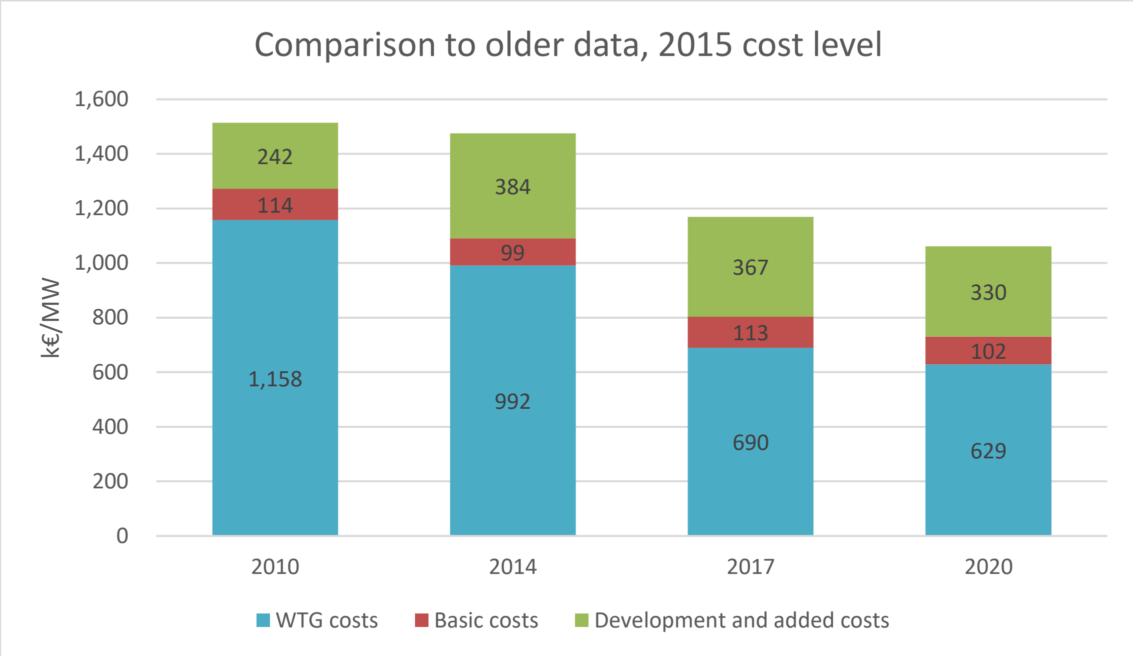

Figure 18 Development in average costs for "Køberets" projects together with 2020 estimate. Basic is foundation, roads and internal grid, the needed "hardware" in addition to the turbines. Development and added costs cover land rent, neighbor compensations and purchase of neighbour settlements and old turbines if such on the site or nearby. Grid connection costs are not included.

Note the WTG cost is reduced 45% from 2010 to 2020. The specific power has decreased 19% in same period, and thereby the production value of the cost reduction is even higher.

Prediction of cost in the period from 2020 to 2050

Onshore wind turbines can be seen as off-the-shelf products, but technology development continues at considerable pace, and the cost of energy has continued to drop. While price and performance of today's onshore wind turbines are well known, future technology improvements, increased industrialization, learning in general and economics of scale are expected to lead to further reductions in the cost of energy. Consequently, despite the fact that more than 350.000 MW of onshore wind has been deployed worldwide, onshore turbines are categorized as development category 3; *Commercial technologies with moderate deployment*, with a significant development potential and a considerable level of uncertainty related to future price and performance.

The annual specific production (capacity factor/full load hours) is expected to continue to increase; this is illustrated in Figure 20. The increase in production is mainly expected to be due to lower specific power, but also increased hub heights, especially in the regions with low wind, and improvement in efficiency within the different components is expected to contribute to the increase in production. This development should also be seen in relation to the fact that taller turbines with high capacity factor and low specific power will have higher market value. A study from 2017 [17] indicate that the market value of wind power in the wholesale market can be as much as 4.3 EUR/MWh higher for high capacity turbines than for low capacity factor turbines by 2030. This supports the expectation of higher annual production and lower specific power.

For the 2020 cost estimate, interviews with project developers etc. form the basis of the estimated costs. These data represent quotations that will be financially decided during 2019-20. The major change from the installed projects 2017-18 is the turbine costs, that decreases from 0.7 M€/MW to 0.63 M€/MW. While the new turbines have lower specific power (8% more rotor area/MW), the cost decrease measured in production is higher. This cost level is confirmed by several project developers. It shall be mentioned that for today's projects, the turbine cost and the service agreement shall be seen together. Often cost reductions on the one part can be realised by increasing the other part. Project cost depends largely on timing and volume. One reason mentioned for the cost reduction is production of more components in China.

According to the report "Renewable Power generation cost in 2017", IRENA 2017 [18] the cost of onshore wind turbines has reduced on average by approximately 20% from 2010 to 2017, with large geographical variations. At the same time, the cumulative installed capacity increased by approximately 100%. The largest cost reductions have been realized in China and India. Hence, the learning rate for the investment cost for equipment, installation and development is set to 10% for every time the cumulative capacity is doubled. According to Bloomberg New Energy Finance, 2018 New Energy Outlook the capacity of onshore wind worldwide will approximately double in each of the periods 2020-2030 and 2030-2050. Hence, 10% learning rate is assumed from 2020-2030 and 10% from 2030-2050 within which the largest decrease happens between 2030 and 2040. Grid connection is assumed to be 5% of total investment costs (including land, decommissioning of existing turbines and other costs). The reduction rates can be seen in the table below and the resulting investment costs is illustrated in figure 18.

	2020-2030	2030-2040	2040-2050
Equipment	-10%	-8%	-2%
Installation and development	-10%	-8%	-2%
Grid connection	-5%	0%	0%
Rent of land	0%	0%	0%
Decomissioning of existing turbines	0%	0%	0%
Other costs (i.e. compensation of neighbours, etc.)	0%	0%	0%

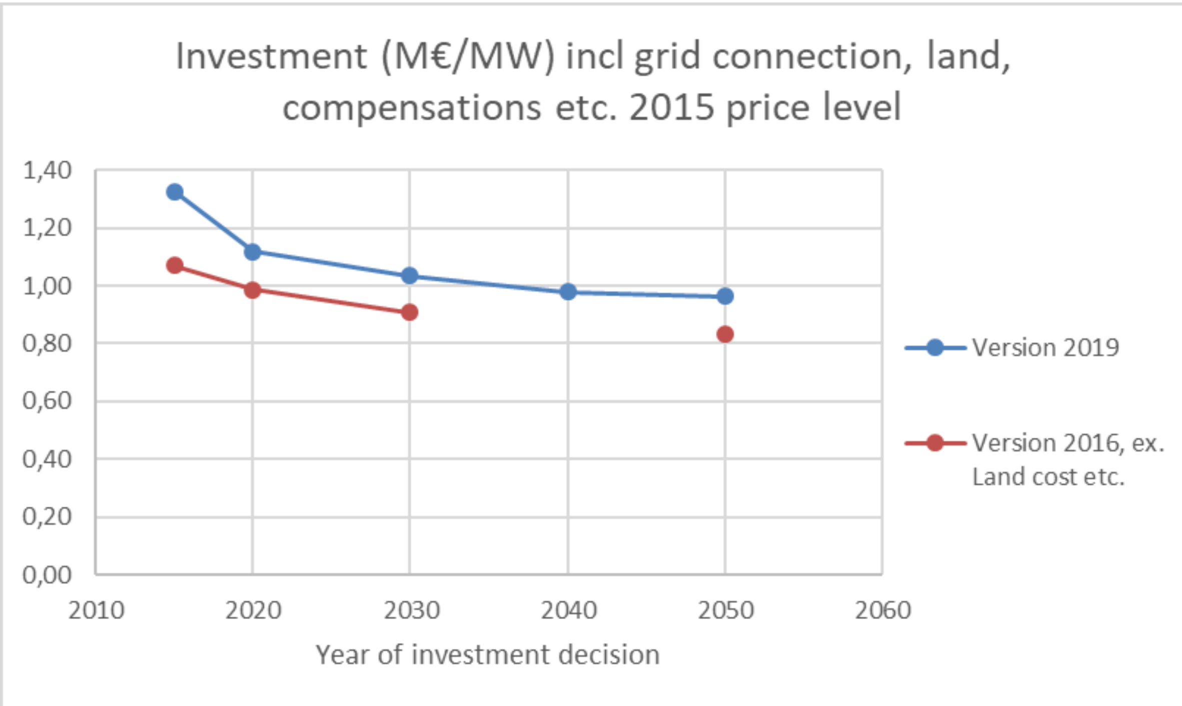

Figure 19 Expected development in investment costs, Ver.2019 inclusion of land and neighbor compensations explains the increase

In figure 19, the development in expected full load hours and specific power is illustrated. The low number of full load hours in 2015 could among other things potentially be due to an attractive subsidy regime in that period, which could have allowed for less attractive projects to be realized. The estimated full load hours in 2020 and onwards represents the full load hours of the expected average available technology and the average available wind resource. The increase after 2020 is mainly related to the decrease in specific power and higher hub heights which in January 2019 is limited to a maximum of 150 m total height by regulation. There will roughly be 2% increase by 5 m hub height increase and 1.5% increase by lowering the specific power 10 W/m2. The dominating factor is although the location of the project (wind resource), where the surface roughness is dominating the wind resource variations in Denmark. Changing a location from a roughness class 2 to a roughness class 1 location will give roughly 15% increase in FLH.

Although the tip height limitation of 150m is expected removed during 2019, the 2020 projects still are assumed to respect that limit, while the planning work is done based on this limit. Only projects which already has most of the planning process settled, can be assumed decided in 2020.

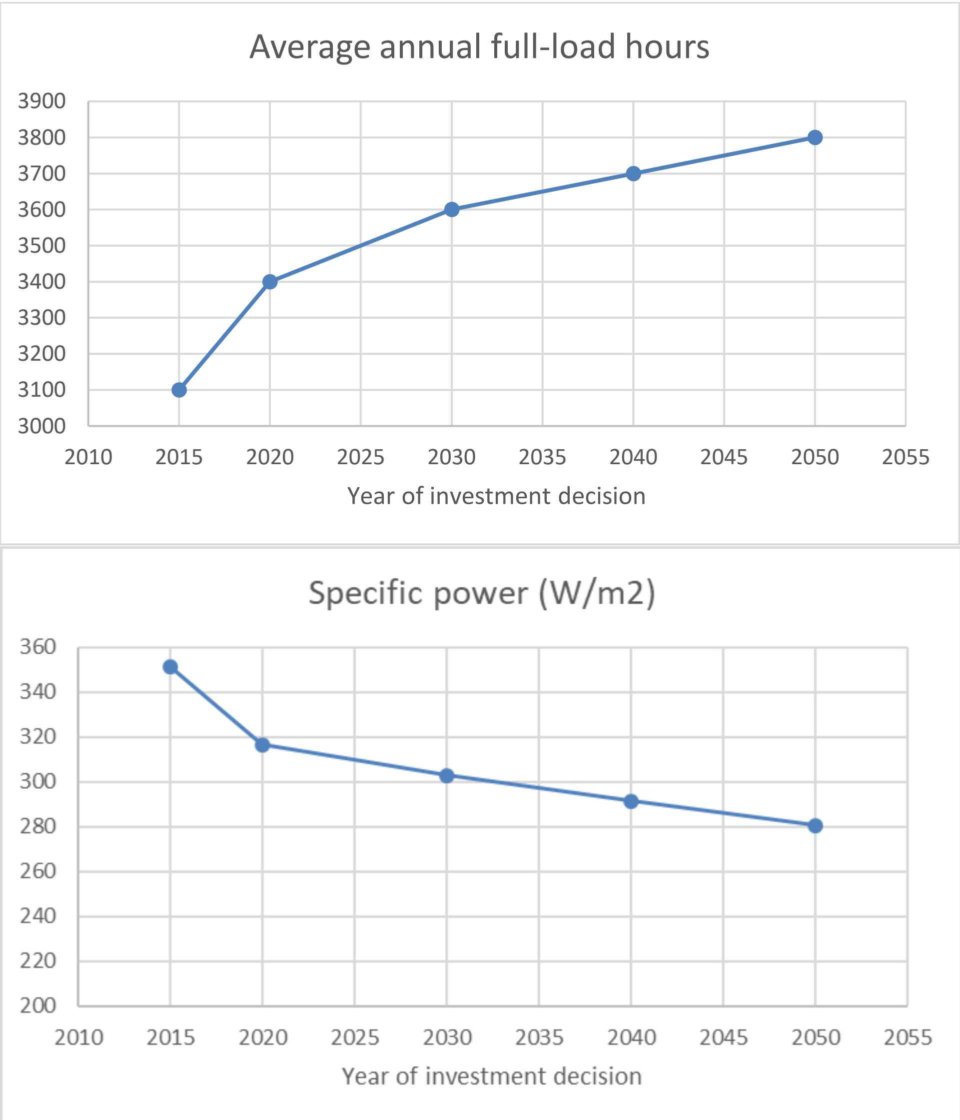

Figure 20 Expected development in production (full load hours (FLH)) and in specific power for on shore wind turbines located in DK.

For the O&M costs, the service agreement is the major part. 70% according to statistics from 12 2017-18 projects. Here a cost reduction of approximately 50% is seen compared to the previous version of the catalogue. This is confirmed by several project developers. Better control of the turbines (less loads), better knowledge on the real costs (more experience means that smaller safe margins are needed as previously) and cheaper spare parts (made in China) are possible reasons for the large cost decrease of round 40% compared to 2016 version of catalogue. The updated O&M cost projections can be seen in figure 20.

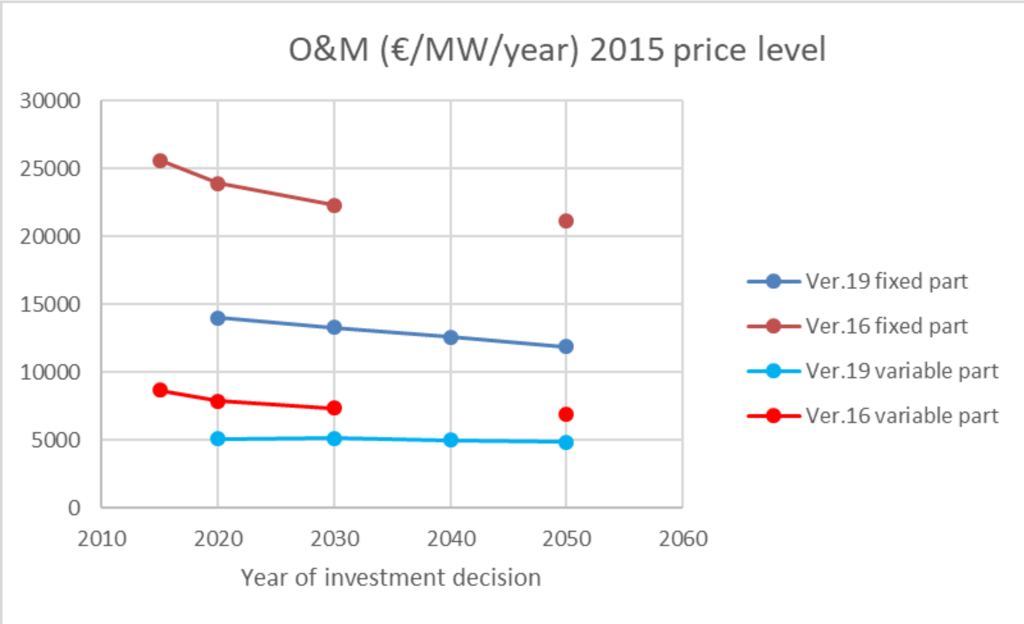

Figure 21 Expected O&M cost, divided into fixed and production dependent (variable, app. 25% of all O&M costs)

Note land lease costs are not included in above, these are assumed part of Capex.

In practice, many wind farms will act in the electricity market with a marginal cost of 0 øre/KWh (thereby assuming no variable O&M). However, in the long run this is not assessed to be a sustainable strategy as some of the moving parts will be worn down with the production and the service fee will scale with production for the service contracts entered later years, at least 5 year back in time. Hence, it is assumed that O&M costs consist of both a fixed and a variable part.

Uncertainty

As mentioned before the onshore wind technology is quite mature. However, due to improvements in technology and cost reductions, the prediction of future reductions in cost of energy is affected by some uncertainty. Especially it must be noted regarding cost development that many other factors than learning curves can affect the cost development, such as the market situation, costs of rare earth minerals, iron, cobber etc. The development in full load hours is affected by the geographic locations of the majority of the turbines to be installed, and it can be increased considerably if larger total heights will be accepted in the future.

Future demands, onshore

In the future it could be expected that the onshore wind turbines will be met with

- Higher environmental protection demands like noise or reduced visibility of aviation light marking or less visibility in general (colouring).
- More demands on participation in grid regulation.

Additional remarks

Recently, the technical lifetime of a wind turbine has been assumed to be 20 years. Recent investigations and real-life experiences indicate longer technical lifetimes [19, 20, 21]. For turbines installed in the coming years lifetimes of 25 years are expected. In the longer term (2030-2050) lifetimes of up to 30 years could be expected.

Domestic wind turbines (micro wind or small-wind turbines)

Domestic wind turbines are micro-wind or small-wind turbines with a capacity up to 25 kW. According to the regulation in Denmark domestic wind turbines (up to 25 kW) must be located in close proximity of a house (within 20 m from building) [23] and must follow the same demands for noise as large turbines [23].

The capacity factor of small wind turbines varies a lot dependent on the local conditions. The turbines are often located close to buildings and trees, which will reduce the annual production from the turbines. The specific power will as for the larger turbines have an impact on the capacity factor and so have the relative low hub height. An average capacity factor of 18% (approximately 1600 full load hours) is assumed in this study. There are no public available statistics for confirmation of this though, while domestic turbines only report sold power whereas in-house consumption directly from turbine is not registered.

Data sheets

Technology	20 Large wind turbines on land										
Year of final investment decision	2015	2020	2030	2040	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data						Lower	Upper	Lower	Upper		
Generating capacity for one unit (MW)	3,1	4,2	5	5,5	6	2,0	6,0	1,5	8,0	A1	3
Average annual full-load hours	3100	3400	3600	3700	3800	2000	4000	2000	4500	A, L	3
Forced outage (%)	3,0%	2,5%	2,0%	1,8%	1,5%	1,0%	5,0%	1,0%	5,0%	B	4
Planned outage (%)	0,3%	0,3%	0,3%	0,3%	0,3%	0,1%	0,5%	0,1%	0,5%	C	4
Technical lifetime (years)	25	27	30	30	30	25	35	25	40	D	14
Construction time (years)	1,5	1,5	1,5	1,5	1,5	1	3	1	3	E	4
Space requirement (1000m2/MW)	---	---	---	---	---	---	---	---	---	F	
Regulation ability											
Primary regulation (% per 30 seconds)										G	
Secondary regulation (% per minute)										G	
Financial data (in 2015€)											
Nominal investment (M€/MW)	1,33	1,12	1,04	0,98	0,96	0,77	1,16	0,80	1,19		16, 2, 4
- of which equipment	0,89	0,71	0,64	0,59	0,58	0,57	0,86	0,46	0,69		25
- of which installation/development	0,12	0,09	0,08	0,08	0,07	0,07	0,11	0,06	0,09		25
- of which is related to grid connection	0,06	0,05	0,05	0,05	0,05	0,04	0,06	0,04	0,06		25
- of which is related to rent of land	0,09	0,09	0,09	0,09	0,09	0,07	0,10	0,07	0,10		25
- of which is related to decommissioning of existing turbines	0,04	0,04	0,04	0,04	0,04	0,03	0,04	0,03	0,04		25
- of which is related to other costs (i.e. compensation of neighbours, etc.)	0,13	0,14	0,14	0,14	0,14	0,11	0,17	0,11	0,17	I	25,26
Fixed O&M (€/MW/year)	25.600	14.000	12.600	11.592	11.340	11.200	16.800	9.072	13.608	I	25,26
Variable O&M (€/MWh)	2,80	1,50	1,35	1,24	1,22	1,20	1,80	0,97	1,46		
Technology specific data											
Rotor diameter	106	130	145	155	165	90	130	100	150	K	4, 26
Hub height	85	85	100	105	110	85	120	85	150		4, 26
Specific power (W/m2)	351	316	303	291	281	314	452	191	453		
Average capacity factor	35%	39%	41%	42%	43%	23%	46%	23%	51%		4, 26
Average availability (%)	97%	97%	98%	98%	98%	99%	95%	99%	95%		4, 26

Notes:

A1 The capacity is set to 3.5 MW in 2015 and 2020 based on data of current wind turbines and under the anticipation that the maximum height will not exeed 150m before 2020. From 2030 a slight increase in generator size, and hub height is assumed, where the effect of expected removal of present max. 150m tip height.

A The full load hours (annual produktion (MWh) per installed power (MW)) depending on the actual location of the wind farm, wake losses and technological characteristics of the individual turbine. The value is an average for the expected locations of the wind farms. FLH also depends on wake losses, noise reduction and technological characteristics of the individual turbine. The level for 2020 is based on expectations from the November 18 auction winners locations and the 2019 prefered technology choice. For 2030 and 2050 a slight increase is assumed based on decrease in specific power and increase in hub height.

B Modern turbines has typically higher forced outage than older smaller turbines had when they were newer due to more complex technology.
C Planned outage is typically 1-2 service visits a year, with a maximum duration of one work day, but there can also be planned outage due to shadow flicker stop or sector management (protect turbines at given wind speeds and directions, where they are dense spaced).
D The life time depends on the wind conditions; average annual speed and turbulence, relative to the design class of the turbine
E The construction time is the periode from FID to commissioning. But from first "dig" to turbines are in operation less than ½ a year is needed for smaller wind farms (clusters), where the similar periode for larger wind farms will be longer. The planning time from idea to construction starts will typically be 2-3 years, but can be essentially more if permitting problems occour.
F An area of around 50 m x 50 m is needed for a modern wind turbine. Another way of defining the "area use" could be the noise zone, which ranges up to 600-800 m from the wind turbine in worst case.
G Wind turbines can be downward regulated within very short time and can therefore (if the wind is blowing) be used in both the primary and secondary downward regulation.
H 2015 Investment costs are based on a number of prospects for projects published in relation to Køberetsordningen. 2020 investment costs are based on updated data from Køberetsordningen. Note that the investment costs listed here includes construction loan interests
I 75 % of the total yearly O&M costs are assumed to be fixed cost and 25 % are assumed to be variable cost.
K Currently only turbines up to 150 m total height is installed commercially in Denmark because of strict demands to higher turbines. No change in the national regulation is assumed until after 2020. Some test sites allow for larger turbines. Aboard e.g. in Germany turbines with at total higher of 200 m is installed today.
L It is expected that the production (FLH) increase 13% from 2015 to 2020 and 3% from 2020-2030 and 1% per decade from 2030-2050

Technology	Small wind turbines, grid connected (< 25 kW)									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Generating capacity for one unit (MW)	< 0,025				0,005	0,025	0,005	0,025		
Average annual full-load hours	1600	1600,0	1600,0	1600,0	1000	2300	1000	2300	A,J	
Forced outage (%)	3%	3%	3%	3%	2%	10%	2%	10%		
Planned outage (%)	0,3%	0,3%	0,3%	0,3%	0,1%	0,5%	0,1%	0,5%	B	
Technical lifetime (years)	20	20	20	20	---	---	---	---		
Construction time (years)	1	1	1	1	0,5	1,5	0,5	1,5		
Space requirement (1000m2/MW)	0,8	0,8	0,8	0,8	---	---	---	---	C	
Regulation ability										
Primary regulation (% per 30 seconds)	---	---	---	---	---	---	---	---	D	
Secondary regulation (% per minute)	---	---	---	---	---	---	---	---	D	
Financial data										
Nominal investment (M€/MW)	4,0	3,8	3,6	3,4	3,0	6,0	3,0	6,0	E/F	
- of which equipment	90%	90%	90%	90%	85%	95%	85%	95%	E/F	
- of which installation	10%	10%	10%	10%	15%	5%	15%	5%	E/F	
Fixed O&M (€/MW/year)	100000	95000	90000	85000	---	---	---	---	G	
Variable O&M (€/MWh)	---	---	---	---	---	---	---	---		
Technology specific data										
Rotor diameter	8	8	8	8	4	14	4	14	H	
Hub height	18	18	18	18	14	18	14	18	H	

Notes:

A The annual production is very sensitive to conditions at the actual site. Values outside the range is observed.

B The maintenance normally consists of 1 -2 annual service visits.

C An area of around 5 m x 5 m is needed for at small wind turbine. The real "area use" is the noise zone, which ranges up to turbine in worst case.

D Not considered relevant for small domestic turbines.

E Based on information from manufacturers and resellers. The

F The prices depends significantly on turbine size (5 kW - 6 M€/MW; 10 kW - 4 M€/MW ; 25 kW - 3 M€/MW)

G The service cost is assumed fixed to 100€/kW/y.

H Domestic turbines have a maximum total height of 25 m according to Danish regulations.

J No development in the capacity factor is expected, because no changing in the size limitation (legislation) is expected. An crucial and one must expect the turbines is put up at the best positions already. But change in legislation is discussed inclu in overall height and allowance to build turbines further away from the property.

References

[6] Information's from expert workshop held by DEA 27-4-2015.

[7] DTU International Energy Report - Wind Energy, DTU, 2014.

[8] Master data register of wind turbines at end of December 2014, Danish Energy Agency, 2015.

[9] Nielsen, P. et. al., Vindmøllers økonomi EUDP projekt 33033-0196, 2010.

[10] Fixed Speed and Variable-Slip Wind turbines Providing Spinning reserves to the Grid, NREL, 2013.

[11] Sundhedsundersøgelsen [Online]. Available: http://vindinfo.dk/sundhedsundersøgelse.aspx.

[12] M. e. al, Wind Turbines and Health, Journal of Occupational and Environmental Medicine, årg. 56, nr. 11, November 2014.

[13] Vindkraftens påverkan på fåglar och fladdermöss, Naturvårdsverket, 2011.

[14] Life Cycle Assessment of Electricity Production from an onshore V112-3.3 MW Wind Plant, June 2014, Vestas Wind Systems A/S.

[15] Environmental Product Decalaration - SWT-3.2-133, siemens.dk/wind, 2014.

[16] S. Krohn, The Energy balance of modern turbines, December 1997.

[17] Karl R. Haapala and Preedanood Prempreeda, Comparative life cycle assessment of 2.0 MW wind turbines, Oregon State University, USA, 2014.

[18] Increasing the Owner's Value of Wind Power Plants in Energy Systems with Karge

[19] Information from Energinet.dk based on analyses of resent installed projects (2013-14), published under "Købsretsordningen", 2015.

[20] Når all-inclusive service alligevel ikke dækker alt, Naturlig Energi, nov. 2014.

[21] Schwabe, P., Lensink, S. & Hand, M., IEA Wind Task 26: Multi-national case study of the financial cost of wind energy, 2011.

[22] IEA Wind TCP, Impact of Wind Turbine Technology on the System Value of Wind in Europe, Ea Energy Analyses, November 2017

[23] Renewable Power Generation Cost in 2017, Irena, 2017.

[24] Hvor længe holder en mølle, Naturlig Energi, januar 2012.

[25] Green, Staffell, How does wind farm performance decline with age?, Renewable Energy 66, 2014.

[26] Vindmøller lever længere end forventet, November 2010. [Online]. Available: http:/www.ing.dk/artikel/vindmoller-lever-laengere-end-forventet-114251.

[27] Vejledningsnotat om planlovens regler ved opstilling af husstandsmøller, Naturstyrelsen, 2012.

[28] Bekendtgørelse om støj fra vindmøller - BEK nr. 1284 af 15-12-2011, Retsinfo, 2011.

[29] Energiaftalen af 22. marts 2012, http://www.efkm.dk/energi-forsynings-klimapolitik/dansk-energi-forsynings-klimapolitik/energiaftale, 2012.

[30] Minivindmøller i København, Ea Energy Analysis for Copenhagen Municipality, November 2009.

[31] Analysis of ”køberets” projects installed during 2017-18

[32] Interviews with project developers and suppliers