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The economics of wind energy

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ABSTRACT

This article presents the outcomes of a recent study carried out among wind energy manufacturers and developers regarding the current generation costs of wind energy projects in Europe, the factors that most influence them, as well as the reasons behind their recent increase and their expected future evolution. The research finds that the generation costs of an onshore wind farm are between 4.5 and 8.7 €cent/kWh; 6–11.1 €cent/kWh when located offshore, with the number of full hours and the level of capital cost being the most influencing elements. Generation costs have increased by more than 20% over the last 3 years mainly due to a rise of the price of certain strategic raw materials at a time when the global demand has boomed. However, the competitive position of wind energy investments vis-à-vis other technologies has not been altered. In the long-term, one would expect production costs go down; whether this will be enough to offset the higher price of inputs will largely depend on the application of correct policies, like R&D in new materials, O&M with remote-control devices, offshore wind turbines and substructures; introduction of advanced siting and forecasting techniques; access to adequate funding; and long-term legal stability.

Contents

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1. Introduction

Wind energy is called to play a crucial role in the future energy supply of the European Union and of the world. By 2020, around 180 GW of onshore and offshore wind power could be installed in the European Union (estimates from the European Commission [1] and the European Wind Energy Association [2]); meaning between 10 and 15% of the total EU electricity demand. Worldwide, wind energy will also supply a sizeable amount of electricity – around 16% in 2020, according to the forecasts of the Global Wind Energy Council [3]. Yet the factors that determine the economics of a wind energy farm are not well known to many, and there has been an intense discussion on the reasons behind the recent increase of its generation costs after 20 years of steady reduction.

The objective of this article is to discuss the main cost categories of a wind energy investment, pointing out their relative weight and recent trends, and to propose a range of generation costs – both onshore and offshore. We also look into the supply chain constraints that affect the wind energy sector and discuss which the main elements are that have provoked a cost increase of around 20% in the last 3 years. The article places these increases into the more general context of growing generation costs of all electricity generation technologies and debates the usefulness of learning curves as a tool to predict the future trend of wind energy costs. Finally, we present a selection of policies that can reduce the generation cost of wind energy.

Thus, Section 2 of the article offers a range of generation costs for wind energy, both onshore and offshore, based on a consultation addressed to European Wind Energy Association members (EWEA comprises 80% of the wind energy manufacturers worldwide and the most important developers, sub-suppliers and research institutes in Europe) and on a comprehensive review of recent studies. The article makes a distinction between capital costs and variable costs, and analyses their evolution separately; it also carries out a sensitiveness analysis of the generation costs based on changes of the key variables (capacity factor, capital costs, variable costs, interest rate, etc.). This part ends with a discussion on the limited value of comparing the wind energy estimates found in the different studies and of comparing wind energy costs with the costs of other electricity generating technologies, due to an inconsistent selection of cost categories and basic assumptions.

Section 3 engages into the interesting debate of why the wind energy sector costs have increased in recent years and whether we can expect them to drop again. In order to do that, we explore the supply chain of some strategic raw materials and sub-components of wind turbines, and prove that most of the cost increase has been driven by the rise of their prices. The article states that cost increases do not only affect the wind energy sector, but also other electricity-generating technologies.

Some of the variables behind the cost growth can be considered as exogenous for wind turbine manufacturers and developers, a fact that limits the value of the learning curves that have been proposed. Yet, technological change still have a strong role to play in decreasing the overall cost of wind energy, provided that the future R&D efforts are put into the key areas. Also market policies, especially those that transform the level of risk for the developer, can help reduce the overall cost of wind energy through a lower risk premium and cheaper interest rates. These are the issues that we tackle in Section 4.

Section 5 finally concludes.

2. The generation cost of wind energy in Europe: current level and methodological issues

The key parameters that govern wind power costs are:

- Capital costs, including wind turbines, foundations, road construction and grid connection, which can be as much as 80% of the total cost of the project over its entire lifetime.
- Variable costs, the most significant being the operation and maintenance (O&M) of wind turbines, but also including other categories such as land rental, insurance and taxes or management and administration. Variable costs are relatively low and will oscillate around a level of 20% of the total investment.
- The electricity produced, which in turn depends on the local wind climate, wind turbine technical specifications, site characteristics and power generation reductions. The indicator that best characterizes the electricity-generating capacity of a wind farm is the capacity factor, which expresses the percentage of time that a wind energy farm produces electricity during a representative year.
- The discount rate and economic lifetime of the investment. These reflect the perceived risk of the project, the regulatory and investment climate in each country and the profitability of alternative investments.

It is important to differentiate between the costs of the wind farm in terms of capacity installed – total of capital costs and variable costs – and the cost of wind power per kWh produced, which takes into account the wind resource. This article focuses on the latter (cost in €/kWh produced), since it allows us to make a comparison between wind energy and other electricity generating technologies.

Wind farm fuel costs are obviously zero. This is the fundamental difference between electricity generated by wind power and most conventional electricity generation options. For example, in a natural gas power plant as much as 40–60% of the costs are related to fuel and O&M, compared to around 10% for an onshore wind farm.

On the other hand, the fact that wind energy projects require substantial capital investment affects the financial viability of the projects. A developer needs to have most of the funds available (around 80%) at the time the wind farm is built, so capital access and good repayment conditions become essential. Some projects may not come to fruition due to the finance needed during this initial stage, even though, over time, this may be a cheapest option. However, the distinct advantage of wind energy is that, after the installation process and provided that wind measurements have been calculated correctly, the generation cost of this technology is predictable. This reduces the overall risk of a company's or country's power portfolio.

The next sections look into the different costs categories of a wind farm investment and offer a choice of figures for onshore and offshore wind energy.

2.1. Capital costs

The capital costs of wind projects can be divided into several categories:

- the cost of the turbine itself (*ex works*),[1] which comprises the production, blades, transformer, transportation to the site and installation;
- the cost of grid connection, including cables, sub-station, connection and power evacuation systems (when they are specifically related to and purpose-built for the wind farm);

[1] 'Ex works' means that no balance of plant, i.e. site work, erection, foundation, or grid connection costs are included. Ex works costs comprise the turbine as provided by the manufacturer: the turbine itself, blades, tower, transport to the site and installation.

- the cost of the civil work, including the foundations, road construction and buildings;
- other capital costs, including development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition) and monitoring systems.

As explained in the previous sub-section, wind energy is a capital-intensive technology, so most of the outgoings will be made at this stage. The capital cost can be as much as 80% of the total cost of the project over its entire lifetime, with variations between models, markets and locations. The wind turbine constitutes the single largest cost component, followed by grid connection.

After more than two decades of steady reductions, the capital costs of a wind energy project have risen by around 20% over the past 3 years. The results of our survey show that they are in the range of 1100–1400 €/kW for newly-established projects in Europe. These costs are sensibly lower in some emerging markets, notably China and in the United States of America. There are also variations within the European Union.

The reasons behind that spread of values lie on the impact of lower labor costs in some developing countries with manufacturing capacity, the degree of competition in a specific market, the bargaining power of market actors, the national regulation concerning the characteristics of the wind turbine (e.g. the existence of strict grid codes in some regions), the distance and modality of grid connection (including the possibility of having to finance all the cost of a grid upgrade) and the extent of the civil works (which in turn depend on factors such as the accessibility and geotechnical conditions of the site).

With all these limitations, Fig. 1 depicts a tentative cost breakdown of a wind energy investment in Europe.[2]

Fig. 2 illustrates the complexity of the sub-components that make up a wind turbine, and helps to explain why these are the most expensive elements of the investment. Note that the figure refers to an exceptionally large size in the current market (5 MW as opposed to the 2–3 MW machines that are being installed in most of the land sites). The relative weight of the sub-components varies depending on the model.

Other elements, apart from the wind turbine, are needed at the beginning of the project, and they can account for around 18–32% of the total capital costs for onshore projects. Their current level and trends can be summarized as follows:

- Grid connection costs. In the past, most wind farm projects have been connected to the distribution voltage grid (8–30 kV) through low to medium voltage transformers. However, it is becoming more common for wind farms to be connected to the transmission network, which results in higher costs. Additionally, the regulation defining who bears the connection cost and – if needed – the upgrade of the line differ in each country. In some places, the transmission system operator will take care of part or all the grid costs. In others, the developer will have to pay the full connection cost plus the upgrade of the line if the regulator considers that this is necessary. Grid connection prices can be regulated and transparent, or can be subject to substantial uncertainty. All this entails different levels of grid connection costs but a general upward tendency (e.g. around 115.24 €/kW in Spain in 2006 and a 13.8% increase in 2007/2008 [5]) has been found in most EU countries. As explained in Fig. 1, grid connection costs (including the electrical work, electricity lines and the connection point) are equivalent to around 12% of the total capital cost.
- Civil works. The situation is more heterogeneous for this category. Some countries, like Spain report a gradual reduction, which they attribute to the economies of scale that arise when the number and size of the wind turbines per wind farm increases. However, in the United Kingdom [4] the infrastructure costs, including civil works, are expected to remain stable in real terms up to 2020, whereas in other countries like France they are on the increase.
- Other capital costs. The elements that make up this category include development costs, land costs, health & safety measures, taxes, licenses and permits, etc. They may be quite high in some areas due to stringent requirements, such as environmental impact assessments. The institutional setting, particularly spatial planning and public permitting practices, have a significant impact on costs (as well as whether a wind farm is actually built). Generally speaking, there is a learning curve for the areas in which wind projects are developed and consequently many regions can benefit from substantial productivity increases if regulatory and administrative systems are adapted to accommodate wind power development.

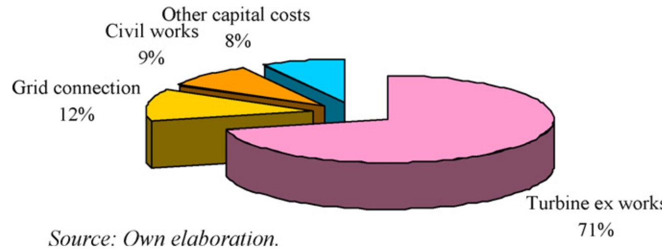


Fig. 1. Estimated capital cost distribution of a wind project in Europe.

2.2. Variable costs

Wind turbines, like any other industrial equipment, require operation and maintenance (O&M), which constitutes a sizeable share of the total annual costs – although the figure is substantially lower than for fossil fuel electricity generating technologies. In addition, other variable costs need to be incorporated to the analysis.

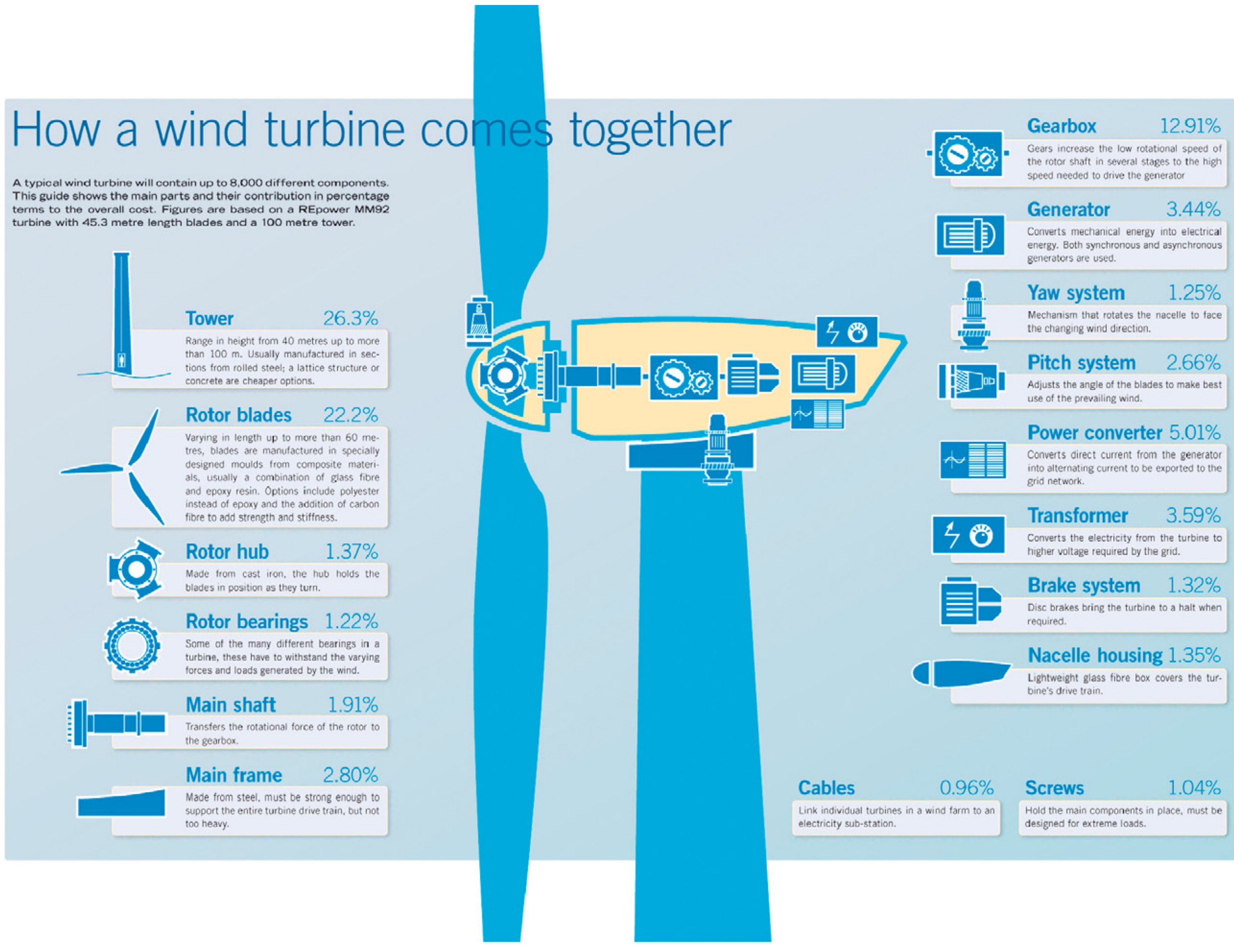
The most important variable costs of a wind energy investment are:

- O&M, including provisions for repair and spare parts and maintenance of the electric installation;
- land and sub-station rental;
- insurance and taxes;
- management and administration, including audits, management activities, forecasting services and remote-control measures.

Variable costs are not as well-known as capital costs, and our survey found significant variations between countries, regions and sites. Few turbines have reached the end of their lifetime, which would allow for a more thorough analysis in this respect.

Certain costs can be estimated easily. For insurance and regular O&M, it is possible to obtain standard contracts covering a considerable portion of the wind turbine's total lifetime. Costs for repair and related spare parts are much more difficult to assess, as this information is not readily available.

[2] The study carried out by the Department for Business, Enterprise and Regulatory Reform (United Kingdom) [4], claimed that turbine ex works accounted for 66% of the capital cost; grid infrastructure for 14%; other infrastructure 17% and planning 3%. The Spanish report from Intermoney-AEE [5] uses the following figures: 72% for the turbine ex works; 11% for grid connections; 9% for civil works and 8% for other auxiliary costs.



Source: Wind Directions, January/February 2007.

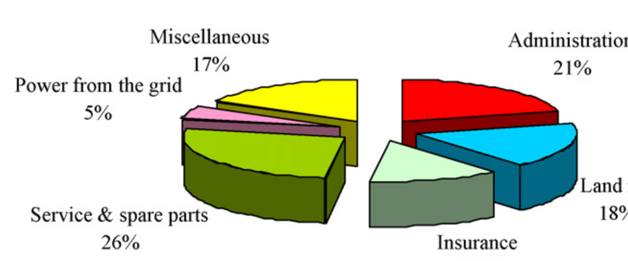
Fig. 2. Example of the main components of a wind turbine and their share to the overall cost in the 5 MW RE Power machine.

At present, one of the wind turbine manufacturers' priorities is to lower the variable costs, mainly those related to O&M, by developing new turbine designs that require fewer service visits, resulting in greater turbine productivity. It is important to note that the downtime of the machines is less than 2% annually.

Based on our own investigation and on a variety of reputable sources like the British Energy Wind Energy Association [6]; the Spanish Wind Energy Association [5]; Erik [7]; Milborrow [8] and [9], a prudent level of variable costs would be between 1 and 2 €cent/kWh over the lifetime of the wind turbine. This would mean between 10 and 20% of the total costs (around 10% in pure O&M activities). As with the other cost categories, the percentages are only indicative.

In Germany, the study carried out by the German Wind Energy Institute, DEWI in its German acronym [10] looked into the trends and distribution of variable costs for German wind turbines installed between 1997 and 2001. For the first 2 years of its lifetime, a turbine is usually covered by the manufacturer's warranty. So, the German study found fairly low total O&M costs (2–3% of the initial investment) over this period, corresponding to around 0.3–0.4 €cent/kWh. After 6 years, the O&M costs increased, accounting for just below 5% of the total investment. This is equivalent to approximately 0.6–0.7 €cent/kWh. Note that the figures were collated a few years ago, so fail to take into account recent price increases or requirements of the newest wind turbines (Fig. 3).

Finally, and with regard to the future development of variable costs, we must be careful when interpreting the results presented previously. Firstly, as wind turbines exhibit economies of scale in terms of declining investment per kW with increasing turbine capacity, similar economies of scale may exist for O&M costs. Secondly, the newer and larger wind turbines have reduced O&M requirements than the older, smaller turbines. Other costs, including those for replacing components, monitoring and insurance may go up, due to a rise in the cost of materials and the greater risks associated with some big wind turbine models. The overall trend, however, according to the limited number of studies that have addressed this issue (for example, the British



Source: [10].

Fig. 3. Variable costs for German turbines distributed into different categories as an average over the time-period 1997–2001.

Department for Business, Enterprise and Regulatory Reform [4]) is of a decrease in costs.

2.3. The wind resource and power generation

The local wind resource is by far the most important factor affecting the profitability of wind energy investments and also explains most of the differences in the cost per kWh between countries and projects. Just as an oil pump is useless without a sizable oil field, wind turbines are useless without a powerful wind resource.

The correct micro location of each individual wind turbine is thus crucial for the economics of any wind energy project. In fact, it is widely recognised that during modern wind industry's infancy (1975–1985), the development of the European Wind Atlas Methodology was more important for productivity gains than advances in wind turbine design.[3] Wind turbines, whose size and characteristics are adapted to suit the observed wind regime, are sited after careful computer modeling, based on local topography and meteorology measurements.

The average number of full load hours varies from location to location and from country to country.[4] The range for onshore installations goes from 1700 to 3000 h/year (averaging 2342 in Spain, 2300 in Denmark and 2600 in the United Kingdom, to give some examples at national level). In general, good sites are the first to be exploited, although they can be located in areas that are difficult to reach.

Theoretical energy generation, based on wind turbine power curves and estimated wind regime, is reduced by a number of factors, like array losses – which occur due to wind turbines shadowing one another in a wind farm – blade soiling losses, electrical losses in transformers and cabling, and wind turbine downtime for schedule maintenance or technical failure. The net generation is usually estimated at 10–15% below the energy calculation based on the wind turbine power curves provided.

2.4. The cost of onshore wind energy

The level and distribution of costs between onshore and offshore wind farms are substantially different. In this section, we deal with generation costs for onshore wind projects. The following section will focus on offshore wind.

For onshore wind projects, and in terms of cost per kWh, an estimate has been made, based on a number of assumptions:

- the calculations are carried out for a new land-based 2 MW turbine;
- the capital investment cost is assumed to be around 1100–1400 €/kW, with a central value of 1250 €/kW;
- O&M costs are assumed to be between 1 and 1.5 €cent/kWh over the lifetime of the turbine; 1.2 €cent/kWh in the medium-term scenario;
- the lifetime of the turbine is set at 20 years;
- the debt/equity ratio is assumed to be 80% and 20%, respectively;
- the discount rate for equity is fixed at 7%, to be repaid over 20 years;
- the discount rate over debt is in the range of 5–10% per year; 7.5% in the medium-term scenario, to be repaid over 12 years;
- the inflation rate is forecast at 3%;
- the number of working hours are set between 1700 (19% capacity factor) and 3000 (35% capacity factor); 2100 in the medium-term scenario (23% capacity factor); and
- risk premium and taxes have not been taken into account.

Based on these hypotheses, the generation cost per kWh of an onshore wind farm today ranges from between 4.5 and 8.7 €cent/kWh. As explained in earlier sections, the wind resource is the factor that has a largest influence over the economics of wind energy. For instance, a wind farm with a capital cost of €1100 will be subject to an increase in generation costs of over 50% if the number of full hours decreases from 3000 to 1700. This percentage variation remains fairly stable regardless of the level of capital costs. If the lifetime of the investment is of only 16 years, and with a capital cost of €1100, the global cost will rise over 10%.

Table 1 shows some interesting figures on the impact caused by a 10% change in a number of key variables, as compared with the central case (capital cost of 1250 €/kWh, O&M of 1.2 €cent/kWh, lifetime of 20 years, interest rate over debt of 7.5% to be repaid in 12 years, capacity factor of 23%).

When increasing/decreasing each of the key parameters by a predetermined rate of 10% we find that it is the number of full hours – that is, the wind resource – which matters the most. A reduction the wind resources of 10% provokes an increase of the generation cost of 8.5%. It is interesting to observe that when the opposite happens (10% increase) the effect is a reduction of the cost of only 6.8%. That is because the cost curve is not a straight line, but a slightly concave one, thus showing marginal decreasing returns. The same can be observed for the other variables.

The second key variable is the capital cost, whose variation of 10% will entail a change of approximately 7.6% of the overall generation cost. This is hardly surprising, given that the wind turbine constitutes the lion share of a wind energy investment.

On the other extreme, the impact of the O&M costs seems to be small ($\pm$2.5%), but the percentage is somewhat misleading, because it does not take into account the (likely) circumstance that higher O&M costs will be accompanied by more frequent downtime of the machines. This will imply a lower number of production hours and, as explained above, a substantial negative impact on the cost per kWh.

2.5. The cost of offshore wind energy

At present, only a limited number of wind farms have been put into operation—22 offshore wind energy projects (1080 MW) and 3 near-shore projects (43 MW). However, there are many projects planned that will change this picture in the short and medium term (figures from EWEA [11]).

The different situations regarding distance from the shore, water depth, and grid construction and connection affect the cost of the offshore wind farm. In general, the greater energy production resulting from better wind conditions than on land does not compensate for the higher initial capital O&M costs. Offshore wind power is, therefore, more expensive than onshore wind power.

In order to understand the economics of offshore wind energy projects, the following key parameters need to be taken into account:

- foundations are considerably more expensive. Costs depend on both the water depth and the chosen construction principle. For a conventional turbine sited on land, the share of the total cost for the foundations is around 4–6%. In the two largest Danish offshore wind farms (Horns Rev and Nysted) this percentage is 21%, and may be even higher in deeper water or with less favorable soil conditions;

[3] The European Wind Atlas method developed by Erik Lundtang Petersen and Erik Troen was later formalised in the WAsP software for wind resource assessment by Risø National Laboratory in Denmark.

[4] Full load hours are calculated as the turbine's average annual production divided by its rated power.

Table 1
Sensitiveness analysis (10% increase/decrease) applied to an onshore wind investment.

Capital cost (€/KW)	O&M (€cent/kWh)	Lifetime	Interest rate (%)	Full hours eq.	% diff. with respect to medium scenario
1250	1.2	20	7.5	2100	
1125	1.2	20	7.5	2100	−7.6
1375	1.2	20	7.5	2100	7.7
1250	1.08	20	7.5	2100	−2.4
1250	1.32	20	7.5	2100	2.5
1250	1.2	18	7.5	2100	5.1
1250	1.2	22	7.5	2100	−4.0
1250	1.2	20	6.8	2100	−2.1
1250	1.2	20	8.3	2100	2.2
1250	1.2	20	7.5	1890	8.5
1250	1.2	20	7.5	2310	−6.8

- the construction and installation techniques are less developed than for onshore projects. This has an impact both in terms of cost and of reliability. The visible efforts that are being made in R&D are expected to bring these costs down;
- O&M costs are substantially higher than for onshore projects. The higher cost of transport, as well as reduced site access, due to wave and weather conditions are the main causes. Having an efficient O&M strategy is extremely important for keeping costs down. O&M costs can constitute up to 30% of overall costs for offshore wind farms;
- electrical connections between the turbines, and between the farm and the onshore grid, generate substantial additional costs compared to onshore wind projects. Going back to the example of Horns Rev and Nysted, they accounted for another 21% of the total investment costs. Again, this percentage will rise in deeper or more distant waters;
- environmental analyses tend to be more stringent, sometimes including R&D programs to monitor impact on mammals and other sea communities. With the generalization of offshore wind energy projects, these are expected to decrease in cost and complexity; and
- the investor faces higher risks, which translate into higher interest rates and premiums.

As a consequence, the uncertainty of cost calculation in the case of offshore wind is higher than for onshore wind. Today a range of between 1800 and 2500 €/kW can be used. This entails generation costs of 6–11.1 €cent/kWh.

The graph below shows a tentative cost breakdown for an offshore wind farm in the United Kingdom, and is based on a recent report published by the Department for Business, Enterprise and Regulatory Reform, formerly Department of Trade and Industry, DTI [12]; which took primary data from the existing offshore wind farms in that country. As always, these percentages will differ from country to country and from project to project (Fig. 4).

Economies of scale will play a fundamental role in the future evolution of costs and so the expected second round of investments in the United Kingdom and the announced plans in Germany, Denmark, Spain and Sweden will improve medium and long-term performance.

2.6. Some methodological issues

When trying to compare our results with those coming from other sources, we find major obstacles caused by the lack of a universally agreed set of cost categories and by the application of contradictory hypotheses regarding the items that should be included in the analysis and the ones that should be left out. The problem affects both capital and variable costs, although is more important for the latter.

For instance, under the heading of "variable costs" some studies only cover O&M costs, while others add the management and administration costs, the land rental, the forecasting services and the periodical taxes that need to be paid. As explained in Section 2.2 of this article, O&M explain around 50% of the variable costs – according to our classification – and thus the exclusion of one or all the other elements will have a noticeable impact on the global generation cost reported.

The national/regional/local policies will determine whether the wind energy developer has to pay the full cost of the grid connection and upgrade, the extent of the civil works, the content of the environmental impact assessment and the level of taxes. While it is fair that these different policies are reflected in the generation cost of a wind energy investment, they will make comparisons more difficult. Moreover, and with a view to ascertain the long-term cost tendency of wind energy, one would need to distinguish the cost elements that depend on the wind resource and on the technological improvements from those cost elements that are determined by the energy/taxation policy of the area where the wind farm is placed.

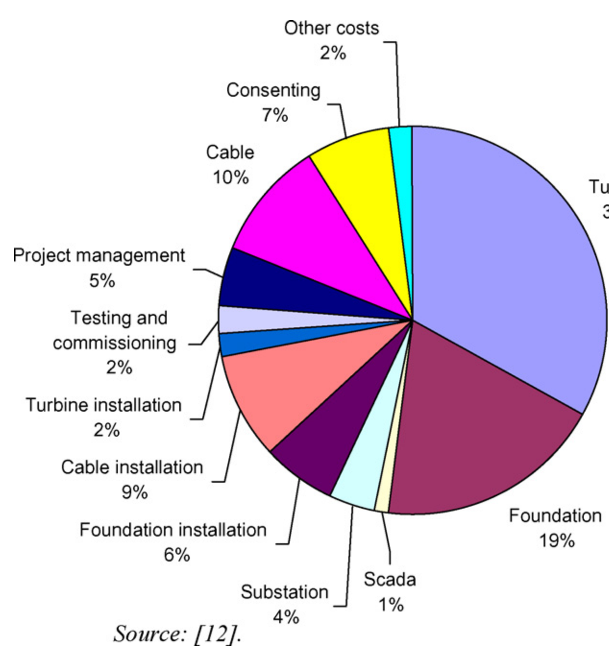


Fig. 4. Estimate of capital cost breakdown for an offshore wind farm.

Other variables must also be discussed among the experts and an agreed baseline scenario should be worked out. The lifetime of an onshore wind farm is generally assumed to be 20 years, and 25–30 years for an offshore wind farm. However, some studies are based on different time-spans, or presume longer or shorter periods for individual components. The Dutch Research Institute ECN (http://www.ecn.nl/en/wind/additional/special-projects/) has got a public-access model which works with a 15 year lifetime. This contrasts with the International Energy Agency model and with our own model, which apply a 20 year lifetime. Other models use timeframes of between 16 and 24 years for onshore and up to 40 years for offshore wind energy.

Finally, we would like to draw the attention on a different problem, which is the cost comparison between electricity produced with wind energy and electricity produced with other sources. The elements that are incorporated to the cost calculation models tend to be slightly different and this has a large impact on the figures that are presented. For instance, very few cost calculations for coal, hydro and nuclear plants take into account the cost of dismantling the installation after the end of its operation. But dismantling costs are a major issue for those technologies, which in some instances have to include the recuperation of derelict land. It is simply not fair to leave them out of the analysis. In the case of nuclear plants, the treatment of radioactive waste is systematically deducted and this provokes a bias in the cost figures that they present.

More subtle is the method chosen to cope with the problem of long-term uncertainty, for instance in the future price of oil and natural gas. The traditional way to handle this uncertainty is to assume different discount rates for the investment. Low discount rates will reflect the higher risk of growing fuel costs, while high discount rates will reflect a low risk level. Institutions like the International Energy Agency [13] then present a list of generation costs for all technologies at a given discount rate, according to a set of pre-defined scenarios – low, medium and high risk scenario – and compare the generation cost of the different options when the discount rate is set at 3%, 8% or 13%.

But not all the technologies face the same uncertainty and so each technology should have its *own* discount rate. Wind energy, being a low-risk option, should have a high discount rate (thus a higher net present value and a lower generation cost); while natural gas plants and other fossil fuel options will have to reflect the higher likelihood that their generation cost will grow in the future. An abundant literature has looked into this issue (Awerbuch [14,15]; Bolinger and Wiser [16]; Bolinger et al. [17]; Kahn and Soft [18]; Roberts [19]). The aim of this article is not to review them in depth, but must at least point to the existence of this fundamental barrier to the cost comparison of electricity-generating technologies and express the convenience of addressing it as soon as possible.

3. The supply chain and its relation with the recent increase of wind energy costs

The booming demand for wind energy projects puts pressure on the supply chain. In addition, fast-growing economies such as China are pushing the cost of raw materials upwards. These include steel, copper, lead, cement, aluminum and carbon fiber, all of which are found in the major sub-components of wind turbines. Since 2004 copper prices have risen by over 200%; lead prices have increased by 367%; steel prices have doubled; aluminum prices have increased by 67%; and acrylonitrile, which is used to produce carbon fiber, has increased by 48% over the same period.[5]

[5] Data from the London Metal Exchange (LME). http://www.lme.co.uk/.

The objective of this section is to explain the role that these causative factors have played in the recent reversal of the cost trends of wind turbines and how and when they will be dealt with.

3.1. Supply chain

On the supply side, there have been bottlenecks in gearboxes and bearings, with a contributory factor being the dramatic increase in the size of turbines, which has severe implications for the supply chain. Another key factor is the price, availability and quality of raw materials. Examples of raw materials that have undergone substantial price increases are steel (used in towers, gearboxes and rotors), copper (used in generators and cables), carbon (used in rotor blades) and cement (used in foundations and towers).

The underlying issue here is that it was difficult to predict that so many world markets would enlarge simultaneously. Increases in component supply require a major investment in machinery, with up to 2 years lead-in time. Our survey found that most manufacturers are substantially expanding their production lines; in some cases, the reaction has been to vertically integrate supply-chain activities and to set up long-term contracts with sub-suppliers.

3.1.1. Blades

These are a crucial component, requiring sophisticated production techniques. Global supply used to be dominated by an independent blade maker, although many major turbine manufacturers produce their own blades. There is no shortage of supply at present, but the availability and price of carbon fiber – a major sub-component for large blades – remains a problem. Several carbon companies have entered the wind energy market to address this problem.

3.1.2. Gearboxes

Most turbine manufacturers have traditionally outsourced their gearboxes to a shortlist of six or seven independent companies. The situation changed somewhat in 2005 and 2006, with several acquisitions, as well as new players and concepts entering the market.

Nonetheless, gearboxes are the component for which most shortages of supply have occurred. The main reasons for this are the limited number of production facilities tailored to the wind energy market, a shortage of large bearings and a bottleneck caused by unexpected repairs to operating gearboxes, including the replacement of bearings. However, most of the manufacturers are already in the process of expanding their capacity and further improving the reliability of their components, with new production lines opening in both Europe and Asia. This should lead to a resolution of current delays in 2008.

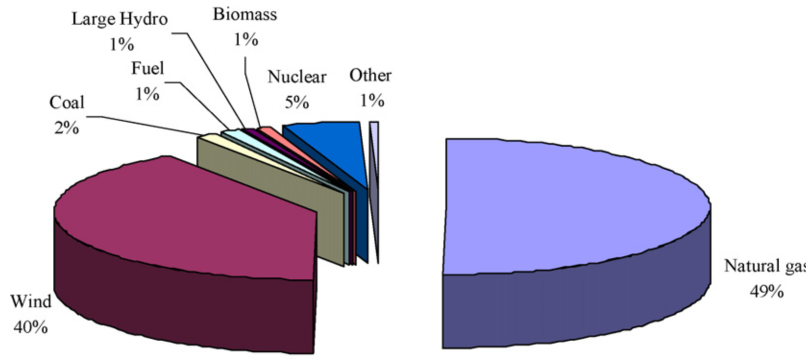
3.1.3. Bearings

There are some shortages of large bearings used in gearboxes and the main shaft. According to BTM-Consult [20], the delivery time for large bearings can be 16–18 months, when no long-term supply agreement is in place. One reason for the shortage is that the boom in the wind industry has coincided with a generally increased level of activity across all heavy industries. For bearings manufacturers, wind represents only a small fraction of their business.

Since 2007, several of the largest bearings suppliers to the wind industry have responded by expanding their production facilities.

3.1.4. Generators

These are supplied to the wind industry by a number of large companies and there are no signs of a shortage. The main stress factor here is high and rising copper prices.



SOURCE: [23].
NOTE: Other includes geothermal, small hydro, peat, waste and other gas.

Fig. 5. New capacity installed in the European Union in 2007, MW.

3.1.5. Cast iron and forged components

This category includes the main frames used to support the rotor hub and nacelle, the hubs themselves and the main shaft, which links the rotor to the gearbox. The market has been affected by the high level of activity in the heavy industry sector, with increased demand for both forged steel and cast iron, whose price and quality have suffered.

3.1.6. Towers

Most turbine towers are made of rolled steel, although some manufacturers are turning increasingly to concrete as a cheaper alternative. Although manufacturing is an increasingly sophisticated process, the basic expertise is more widely available than for other components. Overall, towers are unlikely to create supply problems, but it is still important to keep a careful eye on the price of steel and cement and in the availability of quality steel.

3.2. Demand surges

The biggest factor on the demand side is the industry's dependence on national incentive programs whose shifting patterns are not always easy to predict. The most obvious example of this is the Production Tax Credit (PTC), which has been a major influence in encouraging the wind industry in the United States.

In 2004, the demand in the United States wind energy market was for just 389 MW of new capacity. The previous PTC period expired at the end of 2003. However, with the revival of the incentive at the end of that year, investment took off again, making 2005, 2006 and 2007 record years of 2500 MW, and creating a massive surge in global demand for wind turbines. The effect has also been to encourage turbine suppliers to target the US as a priority, effectively siphoning off turbines from European manufacturers, which could have been destined for other markets.

The growing interest in wind energy projects in many countries of America, Asia and Europe is reducing the impact that one specific legislation change may have on the industry, but can still put the production chain under stress. The recent policy developments, notably of the European Union with the approval of a target of 20% RE consumption by 2020 [21] should guarantee a sustained demand for wind energy farms in the short and medium term. This stable framework should foster the entry of new markets agents – something that we are already witnessing with the expansion of traditional energy companies, utilities, components manufacturers – thus increasing the global capacity of the industry and the competition among them.

3.3. Wind energy cost increases in the broader context of other electricity-generating technologies

Although this article is not intended to provide a comparative review of the generation costs across the electricity industries, the conclusions developed in Sections 3.1 and 3.2 will be better understood when inserted in a broader context.

Wind energy costs have augmented in the past 3 years but so have the other power generation technologies. The reasons are certainly not the same – fossil fuel plants suffer the effects of the doubling and tripling of oil and natural gas prices since 2004 – and their long-term behavior will probably diverge, but the fact remains that wind energy investments are as competitive as they were before 2004.

According to Milborrow [9] the generating costs of natural gas, coal and nuclear energy stood at around 4.9, 4.1 and 6.6 €cent/kWh respectively in 2007.[6] These are approximate figures, and may hide several methodological inconsistencies, as it was explained in Section 2.6. Also note that they do not take into account the environmental externalities caused by energy production, mainly but not only CO_2 emissions. Milborrow and to Blanco and Rodrígues [22] prove that the inclusion of a CO_2 price of around 30 €/ton would transform wind energy as the least-cost option.

Fig. 5 on new generating capacity installed in Europe reflects the attractiveness of wind energy, and shows that in 2007 (also in the 2000–2006 period) it was the second preferred investment option in Europe, after natural gas, with 40% of the total new capacity. The remaining technological options have since many years been lagging behind.

4. Long term trends of wind energy costs

4.1. Learning curves

Despite the recent increase in the capital costs of wind power generation, the long-term trends for wind energy have indicated a

[6] Other studies have looked into this issue. In 2004, BP Power carried out a comparative analysis on "the cost of generating electricity", which looked into the same issue. The values that they published were based on cost figures in the 1998–2002 period and thus fail to reflect the rapid changes that have taken place from 2005 onwards. The figures found by them were: 2.2 pence/kWh (3.19 €cent at a exchange rate of 1.45) for natural gas plants; 2.3 pence/kWh (3.33 €cent) for nuclear fission plants; between 2.2 and 2.6 pence/kWh (3.19 and 3.77 €cent) for coal plants – depending on the technology used; 3.7 pence/kWh (5.37 €cent) for onshore wind and 5.5 (7.98 €cent) for offshore wind farms [24].

Table 2
Capital cost of energy technologies assumed for the PRIMES baseline model (as applied in the impact assessment of the European Commission).

	€/kW in 2020	€/kW in 2030	€/kW in 2040	€/kW in 2050
Onshore	826	788	770	762
Offshore	1274	1206	1175	1161

substantial reduction. Today, a wind turbine produces 180 times more electricity, at less than half the cost per kWh than its equivalent 20 years ago (EWEA [1]).

A variety of models that analyze the long-term cost trend of wind, and other renewable energies, have been developed over the past decade, many of which supported by the European Union.[7] The European Commission, in its 2007 Strategic Energy Review [25] presented an amalgam of their main outcomes, as part of its impact assessment on renewables. It shows that the capital cost of wind energy is likely to fall to around 826 €/kW by 2020, 788 €/kW by 2030 and 762 €/kW by 2050. A similar pattern is expected for offshore wind energy (see Table 2).

In the same way, the British Department for Business, Enterprise and Regulatory Reform [12] has commissioned a study by Ernst and Young, which looks at the present and future costs of renewable technologies. For onshore and offshore wind energy, they predict that the upward trend will continue up until 2010. This will be followed by a decrease, once the supply chain bottlenecks are resolved.

A common way to look at the long-term cost trend is to apply the experience curve concept, which analyses the cost development of a product or technology as a function of cumulative production, based on recorded data. The experience curve is not a forecasting tool based on estimated relationships; it merely points out that if the existing trends continue in the future, then we may see the proposed decrease. Still, it is commonly used in most economic sectors, including the energy sector (for example, Harmonn [26] for solar photovoltaic; Claeson and Cornland [27] for combined cycle gas turbines).

Experience curves for wind energy have been drawn up in Denmark (Neij [28,29]), Germany (Durstewitz and Hoppe-Kilpper [30]), the United States (Mackay and Probert [31]) and in a mix of other countries (Milborrow [32]; Ibenholt [33]; Klaassen et al. [34]; Neij et al. [35]; EWEA and Greenpeace [36]; Junginger [37], Isles [38]). An excellent overview of the experience curves for wind and their usefulness can be found in Junginger et al. [39].

Unfortunately, some of these models use non-compatible specifications and so not all of these can be compared directly. Using the specific costs of energy as a basis (costs per kWh produced), the estimated progress ratios in these publications range from 0.83 to 0.91, corresponding to learning rates of 0.17 to 0.09. So, when total installed wind power capacity doubles, the costs per produced kWh for new turbines decrease by between 9 and 17%. The recent study carried out by the DTI [4] considers a 10% cost reduction every time the total installed capacity doubles.

Naturally, the level of R&D, both public and private, will have a significant impact on future costs, and this is where learning curves do not capture the importance of policy support. As it was detailed in Section 3 of this article, the evolution of steel, cast iron, copper and carbon fiber prices is and will likely remain on the rise, thus exerting a negative influence of the long-term costs of wind energy. Thus, the key question is to what extent technological improvements and economies of scale are able to compensate for these unfavorable factors, and what role public policies can play in this process.

[7] For example, TEEM, SAPIENT, SAPIENTIA, CASCADE-MINTS, co-funded by DG Research.

4.2. Policies to improve the cost effectiveness of wind energy

The aim of this section is to propose a choice of policy measures that can contribute to reduce the long-term generation costs of wind energy. Naturally, the measures should concentrate on the variables that most influence the global cost of a wind energy investment. According to Sections 2.4 and 2.5, these variables are:

- capacity factor;
- capital cost, which in turn is driven by the cost of the wind turbine and its different sub-components;
- improvement of remote-control O&M devices, more stable and cheap foundations and improved materials for offshore wind farms;
- access to capital finance, which depends on the maturity of the banking system, the existence of accurate information on the real risks and benefits of wind energy vis-à-vis other electricity generation options, and the stability of the political framework.

Wind farm capacity factors can be increased through the optimization of the size of the wind turbines, the application of advanced materials for blades, the improvement of forecasting and siting techniques, and the introduction of smartgrid technologies that allow higher amounts of wind electricity be put into the grid.

The level of capital cost is very sensitive to the availability and quality of the raw materials and also to the economies of scale of the production process. The capacity of policy makers to influence the quality and quantity of raw materials is limited, but some actions can be taken to promote free trade and competition in the relevant markets. Economies of scale can be achieved by using measures which support the installation of large-scale facilities, as has been done (with notable success) in Denmark, Germany and Spain, and more recently, in China and the US. R&D in new materials, drive-trains, blades, O&M, wind turbine design and increased efficiency will bring further cost reductions in this crucial investment item.

The reduction of offshore wind costs requires a special R&D effort. Offshore technology is newer than onshore and thus the rate of learning and advancement is relatively high. Areas of high priority for research include safety and access to offshore wind farms, new and improved wind turbine concepts, design and fabrication of substructures, new offshore cabling and connection techniques, and development of O&M solutions with remote control devices. In addition, policy measures have to be focused to create a solid offshore wind energy market, so that economies of scale can be exploited. Recent laws to promote this technology in Denmark, Germany, Spain and the United Kingdom (with differentiated feed-in tariffs, improved grid access, and in some cases, socialisation of the grid connection costs) can be cited as examples. In the future, the cost of offshore wind energy projects will largely depend on the existence of sufficient international interconnectors, which would permit the integration of this large-scale solution.

With regard to access to capital finance, policy makers can develop appropriate awareness campaigns to explain the benefits and the low risk of wind energy investments; this will encourage banks to fund more wind energy projects and at lower interest rates. They can also make funds available for the development of new initiatives, in the form of subsidized interest rates or preferential capital access. But the best policy measure by far consists of creating a stable policy framework, which improves the prediction of income streams for a wind farm. Long-term certainty on the revenue side is of crucial importance for a business in which approximately 80% of the global cost is spent during the first 2 years. A stable policy framework can be achieved through a renewable energy law (which stipulates aspects such as the remuneration level of wind-generated electricity, rules for connecting a wind farm to the grid, and the removal of administrative and grid access barriers) and through the approval of long-term targets that demonstrate the existence of a political commitment over the lifetime of the investment.

5. Conclusions and the way forward

This paper has presented a range of current generation costs of wind energy investments in Europe, both onshore and offshore, based on a survey carried out among European Wind Energy Association members and the systematic review of available studies. It has also assessed the roles and tendencies of its individual cost components, the usefulness of learning curves as a tool to predict the long-term cost reduction potential of this industry and the role that public policies can play in the economics of wind energy. The next paragraphs summarise the main conclusions that have been reached:

Wind energy is a capital-intensive technology, with the fixed assets (wind turbine, grid connection and civil works) accounting for as much as 80% of the total cost. O&M make up another 10% of the expenditure, although there is substantial uncertainty around this category due to the fact that few wind turbines have reached the end of their lifetime, thus limiting the accuracy of any analysis.

The onshore wind energy generation cost is between 4.5 and 8.7 €cents/kWh, with the capacity factor and wind turbine cost being the most influential factors.

The offshore wind energy generation cost can be estimated at 6 to 11.1 €cents/kWh, with the distance from the shore, water depth, and grid construction and connection accounting for most of the cost divergences. Generally speaking, offshore wind energy is located higher in the learning curve and thus susceptible to greater cost reductions in the medium term.

The generation costs of wind energy have increased by 20% in the past 3 years, driven by a combination of rising prices of key raw materials and an unexpected surge in the demand for wind turbines, following the approval of favorable support policies in large markets like the US, China and a second round of European Member States. The growing interest in wind energy projects worldwide will reduce the impact that one specific legislation can have on the industry and keep demand high; the evolution of steel, cast iron, copper and carbon fiber prices is, and will likely remain, on the rise, since the demand for these materials from other economic sectors and geographical areas is not showing signs of exhaustion.

Under these conditions, the lessons that can be extracted from learning curves are of limited value, because they do not capture expected behavioral and structural changes of the industry, nor do they separate the influence of external variables from the internal factors.

An appropriate political framework can certainly decrease the generation cost of wind energy. R&D policies are decisive, and should focus on the optimization of the size of wind turbines, the application of advanced materials for blades, the improvement of forecasting and siting techniques, the introduction of drive-trains, O&M with remote-control devices, and the design of smart grids that accommodate higher amounts of wind energy. As a complement, market measures that increase investment certainty over the 20-year repayment period need to be put into practice: they must include the setting of long-term installation targets to give an order of magnitude of the investment effort needed, clear regulation on grid access and connection costs, the removal of the administrative barriers, and the articulation of an appropriate support payment mechanism.

Last but not least, this paper has identified some areas in which more research is needed: a new study on the costs of offshore wind energy, once more projects are operational; an initiative to agree upon the set of cost categories and basic hypotheses that should be included in analyses of wind generation costs, and comparisons against other electricity generation technologies; a careful assessment of the discount rate that should be applied to each electricity generation technology when trying to capture its long-term income risk; a new definition of learning curves, which makes a distinction between the role played by external variables and the role of economies of scale and R&D actions.

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Appendix A. Publications and reports used for the preparation of the cost estimates

Tables A1 and A2.

Table A1
Summary of the main information sources that have been used in this article at the time of identifying the capital costs and the generation costs of an onshore wind farm.

Study	Capital cost per kW installed	Cost per kWh
Erik (2007)	€900 to €1175	n.a.
Milborrow (2006)	€869 to 1559 €/kW	n.a.
Intermoney-AEE (2006)	€971.67 and 1175.10 €/kW	n.a.
EER forVestas (2007)	1050 €/kW to 1350 €/kW	n.a.
BWEA (2006)	1.52 million €/MW	n.a.
IEA (2005) projected costs of generating electricity, 2005 update, IEA publications	1000–1600 US$/kW onshore (€850–1360) and 1600–2600 US$/kW offshore	n.a.
IEA (2007) annual report, draft-data provided by Governments-	€1365 in Canada; €979 in Denmark; €1289 in Germany; €1050 in Greece; €1200 in Italy; €1209 in Japan; €1088 in Mexico; €1100 in Netherlands; €1216 in Norway; €1170 in Portugal; €1220 in Spain; €1242 in Switzerland; €1261 in UK; €11121 in US	n.a.
UKERC (2007)	n.a.	5.9 €cent/kWh with a standard deviation of 2.5 €cent/kWh
DTI (2007b)	1633 €/kW medium scenario; 1850 in the high scenario; 1422 in the low scenario.	9.3–11.5 €cent/kWh – high and low wind
DTI (2007c)	n.a.	8.1 €cent/kWh to 15.9 €cent/kWh
Bano, Lorenzoni for APER (2007)	1400 €/kW	9.4 €cent/kWh
Wiser, Bolinger for US DOE (2007)	1480 US$/kW (1200 €/kW approximately) projects in 2006; 1680 US$/kW (1428 €/kW) for proposed in 2007	n.a.

Table A2
Summary of the main information sources that have been used in this article at the time of identifying the variable costs of an onshore wind farm.

Study	O&M costs	Other variable costs
Erik (2006)	1.2 to 1.5 €cent/kWh	n.a. (not clear)
Milborrow (2006)	15 to 40 €/kW; 1 to 1.5 €cent/kWh	n.a. (not clear)
Intermoney-AEE (2006)	1.02 €cent/kWh	1.03 €cent/kWh
EER for Vestas (2007)	2.5 to 4 €/MWh; 0.25 to 0.4 €cent/kWh	n.a.
BWEA (2006)	23.25 €cent/MWh	(check)
IEA (2005)	12.50 to 33.8 €/kW	n.a.
DTI (2007b)	61.5 €/kW	n.a.
Bano; Lorenzoni for APER (2007)	1.8 €cent/kWh	n.a.
Wiser; Bolinger for US DOE (2007)	Partial data; 0.68 €cent/kWh for the most recent projects; 1.7 €cent/kWh for older projects.	n.a.

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