Market incentives for system-friendly designs of wind turbines

By Nils May, Karsten Neuhoff and Frieder Borggrefe

Up until now, wind turbines have been designed to generate electricity at the lowest possible total cost, independent of this electricity's market value. With an increasing penetration of wind power in the system, the market value of electricity generated by wind turbines is declining, since wind turbines tend to produce electricity at the same time. For this reason, it will be important in the future to design wind turbines in a system-friendly manner so that a larger proportion of electricity generation occurs in hours with lower wind speeds. This can be achieved with higher towers, longer rotor blades, and generators with comparatively low power ratings.

According to model calculations, a fixed feed-in tariff provides insufficient incentives for such plant designs, which would be especially system-friendly in the context of further expansion of renewable energies. Likewise, direct marketing with a floating market premium does not provide adequate incentives if investors take the current electricity prices as a basis for their planning and project financing. By contrast, in a new instrument that is being proposed here—the so-called "production value-based benchmark approach"—the level of the feed-in tariff is based on the expected future market value of the wind turbine's electricity. In this way, incentives for investments in plants that will be especially system-friendly in the future could already be created in the present. At the same time, questions regarding the actual design and the practical implementation still need to be resolved.

As part of the energy transition, the Federal Government has set the goal of increasing the share of renewables in the total electricity consumption from just under 28 percent in 2014 to 55–60 percent by 2035, and to at least 80 percent by 2050.[1] A particularly large growth is expected in wind energy, and therefore more importance has to be placed upon how the installation of increasingly system-friendly wind turbines can be accomplished. System-friendly turbines tend to be characterized by the fact that they generate more electricity in low wind situations—when the market value of electricity is usually higher—than do conventional wind turbines, which are designed for maximum electricity production. As a result, system-friendly turbines help to keep the total cost of the electricity system as low as possible.[2] This is technically realized through taller plants, longer blades, and smaller generators (Box 1).[3] DIW Berlin analyzed to what extent these system-friendly designs can be made attractive to investors through various policy measures.[4]

Expansion of wind power in Germany until now based on EEG and a production volume-based benchmark approach

In 2000, a fixed feed-in tariff for wind power was introduced under the Renewable Energy Sources Act (EEG) with the goal of enabling stable framework conditions for investments with a cost-covering remuneration: Plant operators received a fixed remuneration for every kilowatt hour fed into the electricity grid. In 2012, an option for direct marketing with a floating market premium was introduced: Plant operators must sell their wind

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[1] 2014 Renewable Energy Sources Act, § 1.

[2] Tafarte, P., Das, S., Eichhorn, M., Thrän, D. (2014): "Small adaptations, big impacts: Options for an optimized mix of variable renewable energy sources." Energy, Nr. 72, pp. 80–92.

[3] Similarly, east- and west-facing panels are discussed in this context for photovoltaics. These supply more electricity in the morning and afternoon, and somewhat less around midday.

[4] For further details of the calculations, see: May, N. (2015): "The Impact of Wind Power Support Schemes on Technology Choices." DIW Discussion Paper No. 1485.

Box 1

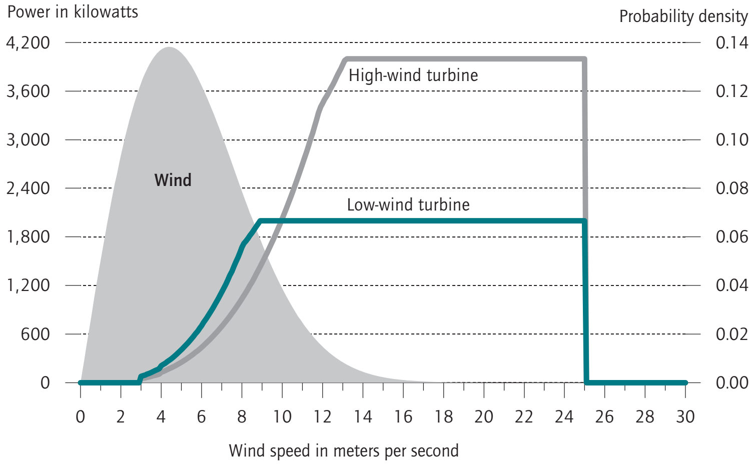
Parameters of wind turbine design

Three technological parameters play an especially important role in determining a wind turbine's suitability for low-wind conditions:

1. Hub height (in meters): At higher altitudes, the rotor blades are exposed to higher wind speeds so that the wind turbine can generate more electricity at all times—especially during periods of low winds.
2. Rotor blade length (in meters): With longer blades, a plant has a larger rotor diameter and is thereby continuously exposed to more wind energy that it can convert into electricity.
3. Generator power (in kilowatts, kW): For generators with a lower power rating, the maximum possible conversion of wind energy to electricity is already limited at a lower wind speed, which leads to a higher number of full-load hours.

Figure

Power curves and frequency distribution of wind speeds at benchmark location



Wind at the benchmark location in 80 meters height.

Source: Own calculations.

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The low-wind wind turbine generates more electricity during the frequent lower wind speeds.

Significant from a system point of view are both the hub height as well as the ratio of rotor diameter to generator power—the so-called "power density"—which is measured in square meters per kilowatt.[1] At a higher power density, the rotor diameter is relatively large, so in relation to the maximum generator power, a relatively large amount of wind energy can be converted into electricity at all times. Thus at any wind speed, a relatively high proportion of the wind turbine's rated power is available.[2] At the same time, this is linked with higher costs. Optimal system designs can be selected depending on the site. The model abstracts from existing certification limitations for low-wind turbines at sites with very strong winds. The figure shows the power curves of two exemplary wind turbines. The power curves specify how much electricity these plants produce at different wind speeds. At lower wind speeds—which occur more frequently—low-wind turbines produce more electricity. At the benchmark location, the exemplary low-wind turbine produces more electricity than the exemplary high-wind turbine 72 percent of the time; the reverse is true in in eight percent of cases.

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[1] An alternative description for the inverse is the specific power rating in kilowatts per square meter.

[2] Molly, J.P. (2011): "Rated Power of Wind Turbines: What is Best?" DEWI Magazin No. 38.

power themselves or via a service provider, receiving the electricity market price plus the difference between the EEG-determined plant-specific tariff and the average market value of the total wind power in Germany.[5] The floating market premium was implemented to further integrate renewable energy into the market and is believed to create incentives for better plant operation—for example, through better production forecasts—and to work towards system-friendly plant designs. If wind turbines are designed so that they produce more electricity in the hours where there are low winds—when electricity tends to be higher-priced—the revenue opportunities increase under the floating market premium.[6] Since the 2014 EEG reform, the direct marketing is now mandatory for all plants whose capacity exceeds 500 kilowatts; from 2016 onward, it will be mandatory for all plants with capacities over 100 kilowatts.

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[5] For details and impacts of the floating market premium on financing costs, see Grau, T., Neuhoff, K., Tisdale, M. (2015): "Mandatory Direct Marketing of Wind Power Increases Financing Costs." DIW Economic Bulletin 21/2015.

[6] For an analytical derivation, see May, N. (2015), l.c.

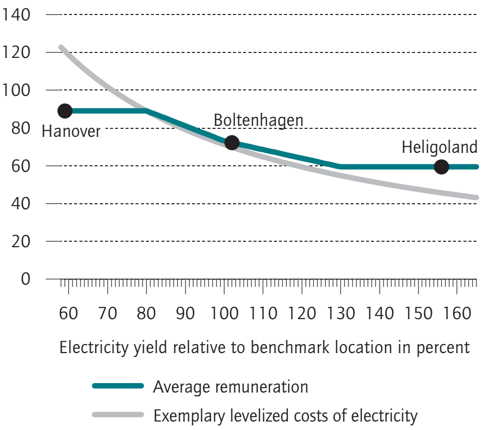
The amount of the remuneration—both in the case of previous feed-in tariffs, as well as the market premium—is adjusted to the respective sites using a so-called “production volume-based benchmark approach.” The idea is to organize the production of wind power in a cost-covering manner regardless of location. It creates incentives to tap into locations with weaker winds, and simultaneously reduces excessive revenues at particularly windy locations. The compensation is divided into two parts: an initial, higher remuneration (currently 8.90 cents/kWh for wind power), and, when necessary, an additional lower remuneration (4.95 cents/kWh) until 20 years after the plant is commissioned. The duration of the higher initial remuneration depends on the site: For example, wind turbines at particularly windy sites receive the higher initial tariff only for a fixed minimum of five years in order to avoid excessive additional revenues. For plants on sites with weaker winds, the duration of the higher initial tariff can be extended for up to 20 years.

The total electricity production of each wind turbine is determined after five years of operation and compared with the so-called “benchmark volume.” The benchmark volume refers to the total electricity production that is calculated for a given turbine using the performance characteristics of a hypothetical reference site—the “benchmark location”. The lower the actual electricity output in comparison to the benchmark volume, the longer the period of the higher initial tariff. Figure 1 depicts the average remuneration using the production volume-based benchmark approach, taking into account the relative electricity production volume of three exemplary sites and one exemplary wind turbine. In relatively windless Hanover, an investor would receive the higher initial tariff for 20 years, whereas in windy Heligoland, the investor would only receive that tariff for the fixed minimum of five years. However, the levelized costs of electricity—i.e. the total discounted costs related to overall electricity output of a plant—in Hanover are higher than those in Heligoland, since the same type of plant produced considerably less electricity.

Figure 1

Average remuneration and costs at different locations

In Euro per MWh



Calculations based on one exemplary wind turbine.

Source: Own Calculations.

The production volume-based benchmark approach facilitates cost-covering remuneration at different locations.

A less expensive energy transition through system-friendly wind turbines

For as long as the share of renewable energies in the electricity system was still low, the power plants’ level of system-friendliness was not that important. With increasing amounts of wind power in the system, the goal should be to maximize not only the quantity, but also the value of the electricity produced. For this purpose, the wind turbines should be designed in such a way that a higher proportion of the electricity production takes place when the overall electricity generated by wind turbines is lower, and the market value of the electricity is correspondingly higher. This can be accomplished through different configurations of hub height, rotor blade length, and generator capacity. The optimal configurations depend greatly on the site. Corresponding political measures should therefore be designed in a fundamentally neutral manner with respect to these parameters.

In general, wind turbines that achieve a higher market value can be characterized as system-friendly. These low-wind turbines can help smooth out the time profile of the electricity demand that is not entirely covered by the feed-in of renewable energy. Thus, other flexible electricity production and storage capacities will likely be needed less. In addition, there tend to be fewer forecast deviations in the case of low-wind turbines, and due to lower production peaks, the network expansion requirements may decrease.[7]

The overall effect of changes in turbine designs and locations would have to be analyzed in the context of the whole future power system. This is not in the focus of this analysis.[8]

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[7] Molly, J.P. (2011): “Rated Power of Wind Turbines: What is Best?” DEWI Magazin No. 38.

[8] Respective analyzes indicate that system-friendly turbines may have a significant additional value, cp. Tafarte, P. et al. (2014), l.c.

Incentives for low-wind turbines depend on the remuneration mechanism

Using an investment model (Box 2), it is possible to determine which plant configuration—depending on the parameters of hub height, rotor blade length, and generator power—investors would select in the case of differing remuneration mechanisms. We examine the effect of four conventionalized remuneration mechanisms:

- a fixed feed-in tariff in combination with the current production volume-based benchmark approach as the base case;
- a floating market premium in combination with the current production volume-based benchmark approach;
- a fixed feed-in tariff in combination with an adjustment in the production volume-based benchmark approach (change of benchmark location);
- a fixed feed-in tariff in combination with the current production volume-based benchmark approach and a newly proposed, so-called "production *value*-based benchmark approach."

As can be seen, all four scenarios are combined with the existing (or, in the third case, a reformed) production volume-based benchmark approach.[9] The results are independent of the question of how the remuneration amount is determined; therefore, in principle, they are also transferable to possible further developments of administratively determined feed-in tariffs or market premiums, as well as to the auction models currently under discussion.

Fixed feed-in tariffs with the production volume-based benchmark approach create insufficient incentives for system-friendly plants

According to the calculations, a fixed feed-in tariff in connection with the production volume-based benchmark approach in its current form creates little incentive for system-friendly design of wind turbines. The results are represented by the example of Boltenhagen (Baltic Sea), a site with fair wind resources (Figure 2).[10] Investors choose a wind turbine with a power density of 3.0 m²/kW. With regard to the assumed electricity prices in 2030, however, a plant with a power density of 3.6 m²/kW maximizes the average value of electricity generation compared to the overall electricity production costs, which is considered system-friendly in this context. This corresponds to a 20 percent increase in the power density; for very windy sites like Heligoland, this deviation even amounts to 49 percent. In the case

Box 2

Investment model

The investment model used here simulates the decision of an investor on the design of a wind turbine that is economically optimal in relation to various sites. The investors maximize the discounted net present value of their investments by selecting from a wide range of turbine configurations that fall between the two extreme designs of a pure high-wind turbine (high generator power rating with short blades and a small tower height) and a pure low-wind turbine (low generator power rating with long rotor blades and a high tower). The investor assumes that the remuneration mechanism is predefined.[1]

For this analysis, various sites are examined: Boltenhagen (Mecklenburg-Vorpommern), Heligoland (Schleswig-Holstein), Schwerin (Mecklenburg-Vorpommern), Bremen, Frankfurt am Main (Hesse), the Kahler Asten (North Rhine-Westphalia), the Feldberg (Baden-Württemberg), and Hohenpeissenberg (Bavaria).

The base year of the calculations is 2013, for which are used the historical wind speeds[2] and electricity prices as well as the reference market values,[3] which the investor is assumed to use for future predictions. A sensitivity analysis was performed using 2012 as the base year and the results are largely the same.

To estimate the longer-term perspective, an electricity price time series for the year 2030 is used. The time series is calculated using an electricity market model from the German Aerospace Center (DLR) (Box 3). Using this model, a total installed onshore wind power capacity of 64 GW and a share of renewable energy of at least 50 percent of gross electricity production are assumed for 2030.

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[1] For details of the investment model, see: May, N. (2015), l.c.

[2] DWD (2015): Historic wind time series. Deutscher Wetterdienst, Offenbach.

[3] European Energy Exchange (2015): EPEX Spot/auction market and network transparency unit: market value/reference market value overview.

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[9] The production volume-based benchmark approach provides not only a geographical diversification of sites, but also has some influence on the turbine design at many sites, which is taken into account in this analysis.

[10] Unless otherwise stated, the results basically apply to the other sites studied as well.

Box 3

The REMix energy system model

The DLR's REMix energy system model is used to determine future price time series. REMix is a dynamic bottom-up energy system model that focuses on the operational optimization of electricity- and heat-generating technologies in conjunction with temporal and spatial load-balancing options.

Using historical weather years, REMix first predicts the hourly future renewable electricity supply in Europe, in high resolution broken down by region, for individual selected base years. A share of at least 50 percent of renewables in gross electricity production is assumed for 2030. Further, it is assumed that the network expansion takes place according to the European Ten-Year Network Development Plans[1] and in Germany according to the network development plans.[2] Next, the electricity supply and demand for Europe are displayed as part of a detailed power plant deployment model. The estimated electricity prices in a region emerge from the marginal production costs of limit-setting power plants, taking into account load-management options and the transmission networks.[3]

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1 ENTSO-E (2012). 10-Year Network Development Plan 2012.

2 50Hertz et al. (2013): *Netzentwicklungsplan Strom 2013: Zweiter Entwurf.* (Grid Development Plan 2013, second draft).

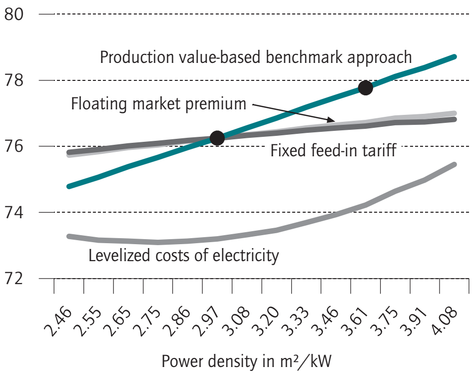
3 The scenarios from the following study form the basis of the present investigation: Scholz, Y., Gils, H.C., Pregger, T., Heide, D., Cebulla, F., Cao, K.K., Hess, D., Borggrefe F. (2014): *Möglichkeiten und Grenzen des Lastausgleichs durch Energiespeicher, verschiebbare Lasten und stromgeführte Kraft-Wärme-Kopplung (KWK) bei hohem Anteil fluktuierender erneuerbarer Stromerzeugung.* DLR Institute of Engineering Thermodynamics Stuttgart, May 2014.

of designs with even higher power densities, the additional costs would exceed the additional electricity value (in 2030). Conversely, the costs per MWh are lower in the case of less system-friendly plants, but the lost potential revenue of the system-friendly low-wind plants is far more significant.

Figure 2

Remuneration and production costs at a location with fair wind resources

In Euro per MWh



Exemplary illustration for Boltenhagen. Unnecessary profits can be avoided by adjusting the absolute level of the remuneration.

Source: Own calculations.

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The production value-based benchmark approach leads to more system-friendly turbines.

Under certain circumstances, floating market premium does not create incentives for turbines that are system-friendly in the longer-term

The model reflects investment decisions made in the context of the floating market premium, assuming the extreme case in which investors assume the unchanged current electricity price profile for the plant's entire lifecycle.[11] The corresponding results suggest that the floating market premium offers few investment incentives for system-friendly wind turbines. The potentially optimal plant from an investor's perspective in this scenario does not change compared that under the fixed feed-in tariff.

This is because in the current electricity system, the proportion of wind power has not yet reached a level in which the wind energy has a very strong impact on the electricity price profile. In other words, a plant design for low winds at the assumed prices from 2013 is not optimal, according to the model, if no significant changes to the electricity price profile are expected—for example, through a higher share of renewable energy and the shutdown of nuclear power plants. This is consistent with the observed new installations: After the introduction of the floating market premium in 2014, the wind turbines erected in Northern Germany were not noticeably system-friendlier than before.[12]

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11 For example, investors might have difficulties predicting the future price formation in the electricity market; they therefore use historical price profiles. This approach is especially common in project financing. For investors' other future expectations, a floating market premium may likewise create incentives for system-friendly low-wind turbines.

12 Only in southern Germany, with its poorer wind conditions, were slightly more system-friendly plants built—but this was probably the case before 2014 as well. See: Deutsche WindGuard (2015): *"Status des Windenergieausbaus an Land in Deutschland"*. Varel, as of 31.12.2014.

In the future, the increasing importance of renewable energy will be more strongly reflected in the price of electricity—with lower electricity prices when the wind is stronger and higher electricity prices in weaker winds. The floating market premium would then give way to the proper plant designs if investors could foresee such price changes and did not have to resort to project financing, in which the strict requirements concerning the security of the future net cash flows would have to be fulfilled in order to have access to cost-effective capital that is low in risk and transaction costs. The current analysis is based on the assumption of the extreme case where investors do not foresee changes in the power price profile or cannot utilize them due to their financing conditions. Hence, regarding the incentives for system-friendly installations which the floating market premium gives, it can be seen as a kind of lower bound. To what extent future changes in the power price profile affect investors' expectations or can be included in their financing is not the focus of this analysis. [13]

At the moment, electricity price fluctuations are rare—particularly upward fluctuations—because the market is characterized by power plants' overcapacities. However, this will change in the medium term, since all of the remaining nuclear power plants will be taken off the grid by 2022. Stronger fluctuations in electricity prices would, however, have a negative influence especially on the production value of less system-friendly wind turbines, which generate a large proportion of their production in stronger winds.

With some exceptions, a fixed feed-in tariff with modified production volume-based benchmark approach leads to system-friendlier power plants

Adjusting the reference site in the production volume-based benchmark approach under the fixed feed-in tariff also changes the incentives: If a reference site with lower average wind speeds is selected,[14] the decrease in the benchmark volume—that is, the energy yield at the benchmark location—from system-friendlier wind turbines is smaller than that of other plants. Consequently, system-friendlier wind turbines achieve a higher benchmark volume at the benchmark location. If the production at the actual site remains unchanged, they attain a smaller percentage of their benchmark volume. Thus they would receive the higher initial tariff for a longer time period, which would be attractive to investors. This measure would have an impact on sites with fair-to-good wind resources. In Boltenhagen—a site that corresponds very well to the reference site—the modified plant configuration increases the number of full-load hours by ten percent compared to the plant chosen under the remuneration model with the conventional production volume-based benchmark approach. [15] The selected plant—as incentivized by the adjusted benchmark location—is system-friendlier than a plant selected under the conditions without any adjustment in the production volume-based benchmark approach: The power density increases by 17 percent to 3.5 m²/kW. For this system-friendlier plant, investors receive the higher initial tariff for a longer period.

However, this possible reform of the production volume-based benchmark approach also comes with disadvantages: For one, even at sites with fair wind resources, this reform will not lead to system-optimal wind turbines. In Boltenhagen, for example, the increase in the power density of a system-optimal turbine would in fact be slightly higher in 2030. In addition, this does not take place in particularly favorable or unfavorable sites due to the minimum and maximum durations of the higher initial tariff.[16] At sites such as Heligoland, Frankfurt, Bremen, and Hanover, nothing changes because plants at these sites, no matter whether the original or the alternative benchmark location is used in the model, receive the higher remuneration for the minimum or maximum duration. Since this applies to around 50 percent of the installed turbines in Germany,[17] the effectiveness of these potential reforms is limited.

A "production value-based benchmark approach" can provide investment incentives for system-friendlier plants

In addition to the existing production *volume*-based benchmark approach, a possible option is to introduce a new "production *value*-based benchmark approach" that embodies the renewable energy expansion goals and their anticipated effects on the electricity price. The expectation that system-friendlier plants can generate greater profits in the future compared to conventional plants would already be explicitly reflected in today's level of remuneration. This is carried out in the following on the basis of the fixed feed-in tariff with the current production volume-based benchmark approach, but in

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[13] Grau, T. et al. (2015), l.c.

[14] Average 5.0 instead of 5.5 m/s, as suggested by Deutsche WindGuard (2014): *Vergütung von Windenergieanlagen an Land über das Referenzertragsmodell.* Commissioned by Agora Energiewende.

[15] The term "full-load hours" positions the actual yield in relation to the plant's installed capacity. It describes how many hours in one year a wind turbine would have to be working at full capacity in order to generate the actual amount of electricity produced during that year.

[16] Defined as places with a benchmark volume of less than 80 percent, or more than 130 percent according to the original reference site definition.

[17] Based on data from 2009 to 2011, Deutsche WindGuard (2014), l.c.

principle it could be transferred to the auction models currently under discussion as well.

Figure 3 shows by way of example the declining market value [of the electricity generated by a specific turbine at 80 meters in high winds in Boltenhagen] in market price simulations of the year 2030. It can be seen that in this future electricity system, the electricity value is significantly higher in low-wind periods. Because of this, the future average achievable electricity prices from turbines designed for low winds are higher than those from turbines that produce a larger proportion of their electricity in high winds. If, however, the value of the electricity produced is not taken into account, but rather the turbine is only designed for the lowest overall electricity production costs, the optimal—from an investor's perspective—wind turbine exhibits a lower power density and is thus equipped for stronger wind speeds.

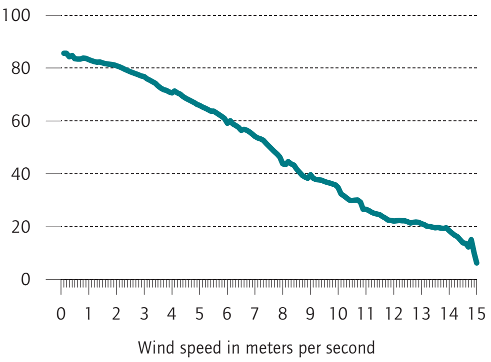
According to model calculations, the wind turbine that realizes the best ratio of market value and overall electricity production costs in 2030 will be a different one than that which is the most profitable in 2013: It will be more clearly designed for low winds with higher power density (Figure 4).

The production value-based benchmark approach aims to create incentives so that the design of wind turbines that fit optimally into the future electricity system will start being implemented now. This is necessary if it is assumed that investors are not able to take projections of future electricity price profiles into account in the planning and financing of projects. Therefore, the level of remuneration—currently starting at 8.9 cents per kilowatt-hour—would be determined for each individual wind turbine in accordance with the projected electricity price. This future market value of electricity production would be calculated for each plant on each site based on a high-resolution wind atlas, publicly available projections of future electricity price time series, and the performance characteristics of various plants. In doing so, the future price would be essential, even now, for determining the plant- and site-specific level of remuneration.[18] Consequently, wind turbines that exhibit a higher market value in the future according to the available electricity price time series would already receive a higher remuneration today.[19]

Figure 3

Market value of wind power in relation to the wind speeds in 2030

In Euro per MWh



Simulation for 2030 based on the REMix model for wind speeds in 80 meters height in Boltenhagen. Wind speeds above 15 meters per second are aggregated.

Source: Own calculations.

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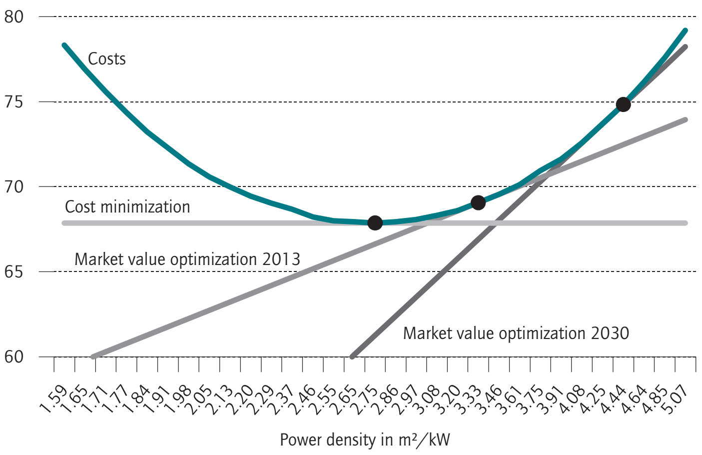
The market value deteriorates with increasing wind speeds.

Figure 4

Production costs and turbine configurations for exemplary cases

In Euro per MWh



Illustrative visualization of the varying turbine configurations depending on the respective perspective. Cost minimization: Electricity is produced at the lowest average costs, independent of its market value. Market value optimization: The value of the electricity is optimized with respect to the given market price profile.

Source: Own calculations.

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Turbines optimized for 2030 have considerably higher power densities (low-wind turbines).

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[18] Whether the design of wind turbines for the future systems of years like 2025, 2030, or 2035—or of multiple years at the same time—should be factored into today's investment decisions is not the subject of this investigation.

[19] The diversification of site selection, which is incentivized by the current production volume-based benchmark approach, could be maintained so that this component of the remuneration calculation remains.

Table

Number of full-load hours at exemplary locations

	Wind speed in 80 meters height in meters per second		
	Low (below 5)	Medium (5 to 10)	High (above 10)
Fair-wind location (Boltenhagen)			
Frequency of wind speeds in percent	30	50	20
Currently chosen turbine	124	1,629	1,502
Future system optimal turbine	152	1,950	1,509
Strong-wind location (Heligoland)			
Frequency of wind speeds in percent	15	38	47
Currently chosen turbine	36	785	3,254
Future system optimal turbine	57	1,226	3,531

Source: Own calculations.

System-friendly turbines achieve more full-load hours in particular during medium wind speeds.

Accordingly, due to the higher electricity prices they achieve, system-friendlier plants can—if the rising share of wind power in the total electricity production leads to further price reductions in the case of high winds—earn larger proportion of their compensation through the sale of electricity, which reduces the EEG surcharge.

Figure 2 shows that a feed-in tariff in combination with the production value-based benchmark approach leads to an annualized average tariff that increases as the wind turbine designs' suitability for low-wind sites increases. For the fixed feed-in tariff and the floating market premium in combination with the current production volume-based benchmark approach, this is the case only to a very limited extent—whereby it should be noted that the analysis of the market premium is based on the extreme assumption that investors assume the current electricity price profile for the plant's entire lifecycle.[20] If one chooses—based on the parameters of the fixed feed-in tariff—a wind turbine that is more suited for low winds, then the incline of the plant's future value for the system (with which the remuneration increases concurrently through the production value-based benchmark approach) in a certain section is greater than the incline of the cost curve. This means that a better ratio of revenues to costs will result with a plant whose design is more suited to low winds. This is the case right up until the system optimum (3.6 m²/kW in Boltenhagen, 2.6 m²/kW on Heligoland) determined in the 2030 model. And from an investor's perspective, this future-system-optimal wind turbine is also economically optimal. The table shows that the number of full-load hours of the system-optimal wind turbine is higher than the number of full-load hours under the fixed feed-in tariff and the old production volume-based benchmark approach, especially in low- and medium-wind speeds.

A feed-in tariff in combination with the production value-based benchmark approach (as well as the existing production volume-based benchmark approach) would offer several advantages: First, it would guarantee that the system-optimal wind turbine for an evolving electricity system is also a commercially optimal wind turbine. Second, it gives investors planning security, because their revenues per kilowatt-hour are known in advance. Third, because this approach does not predetermine any specific designs, neutrality prevails with respect to the turbine parameters. Fourth, such future-system-friendly investments are encouraged at all sites; thus investors will react at both very low-wind and very windy sites, since the remuneration is adjusted based on location.

Alternatively, a floating market premium could give similar results if investors could take accurate projections about the profile of the future electricity prices into account for the design and financing of wind turbines.

Overall, with the growing shares of wind and solar energy, there is the question of which time horizon wind turbines should be optimally designed for, and whether social or private-sector discount rates should be set in the assessment of future costs and revenues. Likewise, the analysis of the production value-based benchmark approach presented here is based on the assumption that an individual turbine fits into the existing system in system-friendly ways. The actual number of differently designed turbines is not considered here. Thus, a very large number of low-wind turbines could also lead to lower prices in low-wind periods. Although a higher number of low-wind turbines may lead to a more efficient design of the electricity system, the establishment of an overall system optimum would be a different issue.

The examination at hand presents the basic mechanism. A discussion about a precise definition of objectives and design possibilities and the associated challenges should not be conducted in all aspects here. In any case, it would be useful to provide a high-resolution wind atlas available for general use.

Conclusion

System-friendly wind turbines can serve as building blocks for the future of an economical energy transition. In an electricity system with a high proportion of

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[20] The line is not horizontal in the case of the fixed feed-in tariff, as well, but rather has a gentle slope, because the production volume-based benchmark approach in its present form already offers slightly differentiated incentives for plant designs.

fluctuating renewable energy, system-friendly wind turbines—as opposed to turbines designed for maximum electricity yields—generate more electricity in low wind, that is, when the value of the electricity is comparatively high. That means the electricity production during high wind is lower, so smaller electricity surpluses arise in windy conditions, when the value of electricity is lower anyway. As opposed to high-wind turbines, low-wind turbines have higher hub heights and/or longer rotor blades, with unchanged or lower generator capacities.

The fixed feed-in tariff that was formerly dominant in Germany primarily provided incentives for investors to produce as much electricity as possible, independent of the moment of electricity production. We demonstrate here that the introduction of the floating market premium provides hardly any incentives for low-wind turbines, assuming that shortsighted investors make decisions for the future based on today's market prices and/or use these shortsighted assumptions about the future for the financing of the turbine. The reason for this is that as of now, the proportion of wind power in the total electricity supply is too small to have a major impact on the electricity market prices.

A slight increase in incentives for system-friendly plant designs could be achieved for sites with fair wind resources by changing the benchmark location definition in the existing production volume-based benchmark approach. Through this, on sites with fair wind strengths low-wind turbines would be more strongly incentivized than other kinds of turbines would be. At the same time, however, the longer-term-optimal turbine design would not be realized, according to the model calculations.

The supplementation of the existing “production volume-based benchmark approach” with a new, so-called “production value-based benchmark approach” could lead to incentives in the present to create plant designs that will be system-friendly in the future. This is achieved by basing the remuneration for the turbines on the expected future market value of their electricity production, whereby the difference between the overall electricity production costs and these turbines’ average achievable future electricity price is minimized. Through the production value-based benchmark approach, system-friendly turbine parameters are not explicitly predetermined. Rather, future market prices are calculated using an electricity market model; based on these projections, incentives are provided for turbines that offer the greatest value for the future electricity system. Compared to the fixed feed-in tariff, the number of full-load hours increases significantly in the calculated examples, especially at sites with low and medium winds. It should be emphasized that such a reform could incentivize system-friendlier turbines at all locations. Before that can happen, however, several issues regarding the specific design and practical implementation of the production value-based benchmark approach, as well as the interactions with the existing production volume-based benchmark approach, would have to be examined.

Similar questions of system-friendly plant design also crop up in the field of photovoltaics, such as to what extent an east- or west-facing arrangement of panels increases system-friendliness.[21] Whether an equivalent tariff based on a production value-based benchmark approach could also incite a system-optimal design for photovoltaic systems is an open research question.

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JEL: Q42, Q55, O38

Keywords: Feed-in tariff, wind turbine technology, wind power investments

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[21] For an example, see: Fraunhofer Institute for Solar Energy Systems ISE (2014): *Effekte regional verteilter sowie Ost-/West-ausgerichteter Solarstromanlagen.* Commissioned by Agora Energiewende.

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Layout and Composition
eScriptum GmbH & Co KG, Berlin

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Sale and distribution
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