With a yield of about 50 TWh, wind energy was the dominant renewable energy generation technology in Germany in 2014 (AGEB 2014). The low-cost wind resource and greater areas of suitable land have meant initially that the north of Germany has seen major expansion of wind energy. Resulting from this is a concentration of wind turbines in the north Germany region which frequently feed into the grid at high capacity at the same time. The merit order effect means this high level of simultaneous feed-in of wind power often has a considerable price-lowering effect on the exchange electricity price.

The technical enhancement of wind turbines has enabled the development of wind farms in inland regions with weaker winds. These turbines may feed into the network at different times compared to installations in northern Germany [Pape et al. 2013]. The question therefore arises as to whether wind turbines which attain lower yields in areas of weaker winds in the south, but which feed into the network at atypical times (due to their different feed-in characteristics) are able to benefit from this effect and attain above average revenues in the direct marketing of wind power generated. If not, regional grants may be necessary to raise the attractiveness of such regions and to compensate potentially higher investment costs.

**Analysis methodology**

To determine the market value factors of wind energy in a future scenario, the capacity time series of wind power generation and the corresponding time series of the spot market prices are required. The latter were generated on the basis of the 2013 European market simulation, and made available by the Federal Network Agency. Assumptions on renewable energy expansion, the growth in the number of power plants and the exchange capacities between market regions comply with the scenario framework in the GDP. The historic weather year 2007 was used for the market simulations and for generating the capacity time series for wind energy. The simulation of wind power feed-in is based upon the COSMO-DE model from the German Weather Service, covering Germany with about 46,000 weather model areas having a grid width of 2.8 km.

**Definition of market value factor**

The market value factor specifies how the value of electrical energy provided differs from the average spot market price. It corresponds to the ratio of actual sales revenue which the installation attains over the year, and the sales revenue which would be achieved with feed-in at the average spot market price.

\[
MWF = \frac{\Sigma \text{stdl. Strompreis} \times \text{stdl. Einspeisung des Energieträgers}}{\text{durchschnittlicher Strompreis} \times \Sigma \text{stdl. Einspeisung}}
\]

Accordingly, a market value factor of less than 1 means on average that below average revenues are achieved in selling the electricity. From 2012 to 2014, the market value factors for electricity generation from wind power on land were between 0.80 and 0.88 [Fernahl et al. 2014].
To eliminate the effect of different yields on the regional market value factors, capacity time series with identical specific yields (here 2,500 full-load hours (FLH)) are generated for all model areas. This occurs with variation in hub height and rotor to generator ratio, provided this level of utilization is achievable with realistic installation parameters. Four wind turbine types with different rotor to generator ratios formed the basis for the variation of installation parameters. Three of the installation models are from the study “Renewable Energy Expansion in Germany at Optimum Cost” [Fürstenwerth et al. 2013]. An installation with about 203 W/m² (Table 1) was selected as another reference installation with a very customized layout for weak wind locations. By interpolating between parameters hub height and rotor-generator ratio (Figure 1), capacity time series for wind energy with the number of full-load hours specified, with simultaneous formation of generation characteristics over time, were generated for every model area, taking these four wind turbine types as the starting point.

Sales revenues are determined by multiplying the hourly wind power generation (of every model area) by the spot market prices for the respective hour for the year. The market value factors for every model area are determined from the ratio of average sales revenues to average exchange electricity price.

Also, an estimation is carried out in which specific investment costs would be required on every model area to attain the 2,500 FLHs specified (in weather year 2007). These figures depend on the wind potential at the location, and so the required design of installations. The investments required are contrasted against the sales revenues determined for scenario year 2023 to gain an indication of the cost-effectiveness of a location in due consideration of regional market value factors.
Market value factors determined

A utilization of 2,500 FLHs was possible on 93% of the model areas across Germany by varying the installation configuration. This number of full-load hours was not achieved on the remaining 7% because the level of wind was too low or too high.

Figure 2 shows the spread of market value factors determined for Germany. The hypothetical average sales revenues of wind power generated by wind turbines with 2,500 FLHs are between 85% and 101% of the average exchange electricity price (taking into account the price time series provided). Similarly, the market value factors range from 0.85 to 1.01. As assumed at the beginning, the south sees higher market value factors than in the north. This is attributable mainly to the feed-in of wind turbines in northern Germany which drive the electricity price down. Wind turbines in the south frequently feed into the grid at times different to installations in the north, and thus attain higher average sales revenues.

The frequency distribution for the market value factors in question can be seen in the histogram in Figure 3. The maximum market value factors (greater than 1) can be seen primarily in Baden-Württemberg, whilst on the North German Plain, mainly lower market value factors with values between 0.85 and 0.90 are determined. At a maximum of 16 percentage points, the spread of market value factors determined this way is relatively low overall.

Capacity-specific revenues

Capacity-specific revenues for the weather year analyzed are derived from the market value factors depicted. They are between 113,000 and 130,000 € / MW, and so differ by a maximum of 17,000 € / MW (Figure 4). Because in this analysis all installations generate the same amount of energy in terms of installed capacity, capacity-specific revenues of installations in the south are higher (in line with the market value factors). The linear relationship means the distribution across Germany corresponds to that of the market value factors.

The methodology adapted here permits a comparison of market

Figure 2: Market value factors of wind turbines in 2023 for 2,500 FLHs and wind conditions of 2007 (in grey areas, it was not possible to attain the FLHs required with the installation configurations given).

Figure 3: Distribution of market value factors over the area of Germany in 2023 for 2,500 FLHs and wind conditions of 2007.
values across Germany. It is clear here that installations in the south feed into the network at higher average prices, and so can attain higher sales revenues than installations in the north for the same energy yield. What continues to be disregarded however is the fact that higher sales revenues are contrasted against higher investment costs - because a weak wind installation attaining 2,500 FLHs in the south is usually associated with higher investment costs than a strong wind installation in the north having the same FLH rating.

**Additional revenue vs. additional cost**

Price estimations were made for individual installation types to assess sales revenue in relation to investment costs. The estimations for investment costs of wind turbines are based on study “Cost Situation for Wind Energy Onshore” [Rehfeldt et al. 2013]. This study investigates the cost structure of wind energy in 2013. For the derivation of cost developments, the trend towards complex structures e.g. with higher towers was included on the one hand, and moderate learning curves presumed on the other. The specific costs for the installation types analyzed are numbered in Table 1 for 2023. The estimation of such a cost development is always associated with a high level of uncertainty. Despite the resolution of the weather model which is already high, the wind potential within a model area can be considerably different locally. In ridge locations for example, much cheaper installations could attain 2,500 FLHs, whilst valley locations would entail higher investment costs. The findings generated this way, and shown below, therefore only represent an approximation. But they do form an adequate basis to estimate the significance of regional market value factors.

Figure 5 shows the specific investment costs of wind turbines distributed across Germany in 2023 which would achieve 2,500 FLHs in weather year 2007. At locations with weaker wind, investment costs rise considerably because more complex turbines with higher hub heights and greater rotors in relation to generator capacity would have to be installed. Specifically in areas where figure 4 promises higher revenues, investment costs are up to 655,000 €/MW higher than particularly windy locations.

Figure 6 illustrates that the higher sales revenues of wind tur-
bines in the south are not high enough to compensate for the addition costs of the installation types required. Sales revenues for installations in the scenario for 2023 are between 5% and 10% of investment costs assumed (weather year 2007). Installations in isolated regions of central Germany attain the highest figures. In south Germany, there are even smaller areas in which revenues are attained which cover in equal share investments in large regions of north Germany. However, revenues in most parts of south and central Germany are not high enough to compensate for the addition costs of installations. This also becomes apparent in the comparison of electricity generating costs of wind turbines in locations with weak and strong wind. For 2013 for a 60% reference location, electricity generating costs were determined to be 43% higher than for a 100% reference location (110.7 €/MWh compared to 77.4 €/MWh) [Rehfeldt et al. 2013, Table 8-3]. Given that market value factors for wind energy in Germany differ by a maximum of 16 percentage points, these differences are not high enough to compensate for higher electricity generating costs.

If the requirement to build installations at locations with weaker wind conditions remains, to decentralize energy supply and to reduce the grid expansion requirement for example, the need for a regionally adopted funding scheme persists - even for a self-marketing model.

Sources

Figure 6: Sales revenues of wind turbines in 2023 as a percentage of their investment costs for 2,500 FLHs and wind conditions of 2007