Eckel, Henning; Hartmann, Stefan and Eggersglüß, Walter

Profitability of small wind turbines

Small wind turbines can contribute to the supply of electricity from renewable resources. They have attracted great interest, especially in the agricultural sector. On the one hand, the target can be an economical one: producing an as large as possible share of the electricity consumed on the farm and thus becoming more independent of electricity price developments. On the other hand, such a move offers a contribution to climate protection.
Following a short overview on site selection, electricity yields and the legal framework this article discusses the profitability of small wind turbines taking into account various exemplary site conditions. It becomes clear that small wind turbines may be profitable through their production of electricity that otherwise would have to be purchased. Preconditions for this are favourable site conditions and a strong temporal correlation of electricity production and consumption.

Keywords
Windenergy, small wind turbines, electricity production, electricity self-supply

Abstract
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There are various definitions for the term small wind turbine. The Bundesverband Windenergie classifies turbines of up to 100 kW generator nominal power as small wind turbines (SWT). In the IEC Norm 61400-2:2006 [1] turbines with a rotor swept area up to 200 m^2 are defined as small. This indicates a generator nominal power of around 60–70 kW.

Discussed in this report are turbines with a nominal power range of 7.5–25 kW. SWTs are available with rotors on a horizontal or vertical axis. Horizontal axis turbines are most common because of their higher efficiency. Where noise plays an important role on a site the quieter-running vertical axis rotors can offer advantages.

Site selection and electricity yield

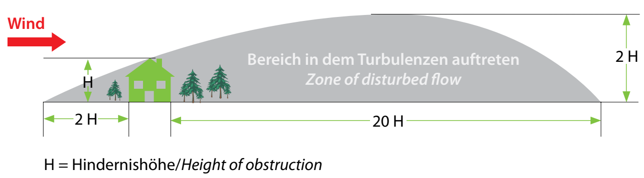
The production potential of a wind turbine depends on four factors: Wind speed has the greatest influence, being applied cubed in the power calculation. Over and above this, the performance coefficient of the turbine (cp), the rotor swept area and air density have to be considered. The performance coefficient of the turbine describes as dimensionless variable the proportion of the energy in the wind which can be used by the turbine. The maximum possible value according to the Betz` law is 0.59. In practice, cp values of around 0.50 are achieved. The site of the turbine plays a decisive role for energy production. Alongside available wind, lesser factors such as distance from buildings and vegetation have to be considered. Especially important is ensuring that the turbine is sited so that the prevailing wind flow to the rotor is unhindered. Hereby, the distance between turbine and obstacles should, as a rule of thumb, be at least 20 times the height of the respective obstacle [2] in order to avoid turbine performance being adversely affected by turbulence (**Figure 1**).

Orientation for possible energy yield, depending on average wind velocity on site at rotor hub heigh,t can be based upon the following calculations:
4.0 m/s => 185 kWh/m² rotor swept area
4.5 m/s => 260 kWh/m² rotor area
5.0 m/s => 335 kWh/m² rotor area
5.5 m/s => 420 kWh/m² rotor area
6.0 m/s => 500 kWh/m² rotor area

Example

With a rotor diameter of 9 m, a rotor swept area of 65 m² and an average wind speed at rotor hub height of 4.5 m/s, an annual yield of around 16 900 kWh can be expected. A more precise estimation of yield is possible with knowledge of the

Fig. 1



Zone of disturbed flow ahead and behind an obstruction (adapted from [3]) wind speed distribution. The relationships in this context represented in **Figure 2** are based on a SWT with 7.5 kW nominal power achieved at 16 m/s and calculated with the MS EXCEL tool "Small Wind Turbine Yield Estimator" [4].

Figure 2a indicates a typical wind speed distribution for a site with an average wind speed of 5.0 m/s. **Figure 2b** presents the progression of the cp value and the turbine performance with increasing wind speed. In this example the peak cp value is achieved at a wind speed of 6–7 m/s.

The periods (h/a) of individual wind speeds at rotor hub height multiplied by the respective related performances from the SWT performance curve (kW) gives the annual electricity output of the turbine, in this example 9 380 kWh/a (**Figure 2c**).

Legislation framework

Under the book of building statutes (BauGB), wind energy turbines are regarded as structures. For this reason a planning permission procedure has usually to be carried out according to the requirements of the building regulations in the respective states.

Meeting noise prevention requirements and avoiding rotor shadow disturbance are usually only possible when the wind turbine is sited outwith built-up areas. Hereby the requirements of §35 BauGB have to be taken account of.

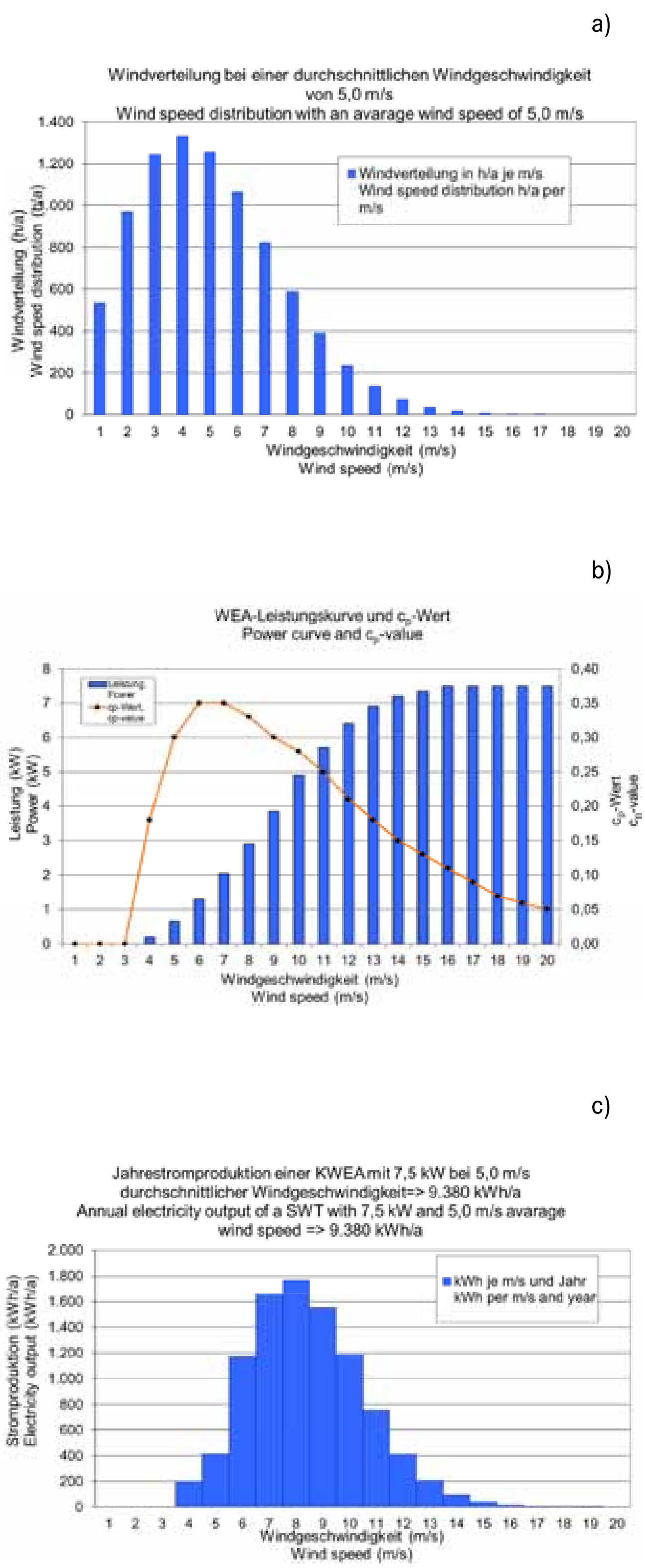
Electricity produced by wind turbines and fed into the public network is paid for under the regulations of the renewable energy law (EEG) [5]. Over at least five years an initial starting payment is made which is 8.93 c/kWh for turbines starting production in 2012. Subsequently the basic payment is 4.87 c/kWh. For turbines under 50 kW installed performance the EEG regulations stipulate that the higher initial rate applies over the entire payment period of 20 years. The payment rate for new turbines is to be reduced every year by 1.5 % but then apply for the entire payment period in each case.

Economic performance

The following economic efficiency analyses are based on data gathered by means of a manufacturer's survey for SWTs of 5–30 kW nominal power [6], conducted by Schleswig-Holstein Chamber of Agriculture. In **Table 1** the range of values is presented. These values form the basis for the economic efficiency analysis models. Three turbine models are defined for the economic efficiency analysis with nominal power of 7.5, 15 and 25 kW respectively. The assumptions for swept area, hub height and required investment are presented in **Table 2**.

Operating costs of a SWT comprise expenditure on servicing and repair plus insurance and administration. From the turbine manufacturers that were asked, operating cost estimations of 28–98 €/kW nominal power and year were given. In that no clear relationship between operating costs and SWT nominal power could be calculated from the recorded data, an average value of 55 €/kW nominal power and year was applied for all turbines for economic efficiency analysis. The most important factors influencing electricity production costs are required in-

Fig. 2



Wind speed distribution (a), power curve and c_p-value (b) and annual electricity output (c) using the example of a 7,5 kW wind turbine with 6,0 m rotor diameter

Table 1

Characteristic values of small wind turbines of different power classes according to manufacturer's specifications [6]

Nennleistung *Nominal power*	**kW**	**5–10**	**>10–20**	**> 20–30**
KWEA-Typen *Small wind turbine type*	Anzahl Stück *Number*	16	7	5
Überstrichene Rotorfläche *Swept area*	m²	15,2–50,0	39,6–78,4	108,0–133,0
Nennleistung/überstrichene Rotorfläche *Nominal power/swept area*	W/m²	156–545	140–323	165–233
Höhe bis Rotormitte (entspricht bei Horizontalanlagen der Nabenhöhe) *Heigth to center of rotor (equals height of hub in case of horizontal axis)*	m	7,5–24,0	13,4–24,0	18,0–24,0
Spezifischer Investitionsbedarf *Specific investment needs*	€/kW Nennleistung *€/kW nominal power*	2.600–9.200	1.902–4.182	2.283–4.000
	€/m² überstrichene Rotorfläche *€/kW swept area*	719–2.727	510–1.162	521–923

Table 2

Model plants

Modell *Model*	**kW**	**7,5**	**15**	**25**
Überstrichene Rotorfläche *Swept area*	m²	28	65	126
Nabenhöhe (Rotormitte) *Height of hub (center of rotor)*	m²	15	19,5	21,6
Investitionsbedarf *Investment needs*	€	33.750	56.250	81.250
Spezifischer Investitionsbedarf *Specific investment needs*	€/kW	4.500	3.750	3.250
Summe Jahreskosten *Total annual costs*	€/a	2.775	4.763	7063

vestment for the plant and expected yields of electricity. For the model economic efficiency analysis, plant depreciation period is 20 years. A general interest rate of 4 % was applied for the capital involved.

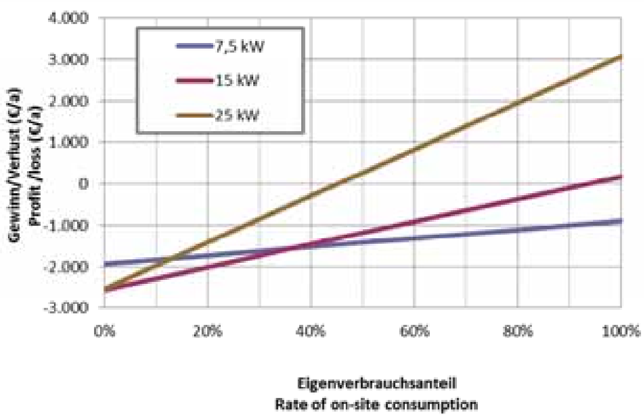
The calculation of electricity production costs for the three model plants was carried out in each case for five different sites defined through their average wind speeds. In relationship with rotor hub height the assumed average wind speed for the most unfavourable site was 4.0–4.3 m/s and for the best site 6.0–6.5 m/s. **Table 3** shows the expected electricity yields, the specific investment requirements based on annual electricity yield and the calculated electricity production costs.

Under the above assumptions, electricity production costs for the 7.5 kW model lay, according to site, between 19.82 and 53.57 c/kWh, for the 15 kW model between 13.20 and 33.21 c/kWh and for the largest model turbine with 25 kW between 9.75 and 23.85 c/kWh.

A specific investment requirement of less than 2.45 c/kWh annual electricity production enabled electricity production costs of under 20 c/kWh. Under these conditions electricity production with a SWT can lead to a positive business result through substitution of bought-in electricity. Hereby an electricity price of 20 c/kWh is assumed.

Taking the example of the average site (Ø wind speed 5.0–5.4 m/s) the economic results for three model plants in relationship to own-consumption proportion is presented in **Figure 3**. For a balanced result, an own-consumption proportion of 45 % must be achieved with the 25 kW plant and 94 % with the 15 kW plant (**Figure 3**). In order to achieve these high own-consumption proportions in practice, the electricity requirement must represent many times the annual SWT electricity production so that the produced electricity can be fully utilised at any particular time.

Fig. 3



Economic performance of small wind turbines as a function of the rate of on-site consumption (average site)

Table 3

Electricity production costs related to site conditions

Modell/*Model*	**kW**	**7,5**	**15**	**25**
Sehr guter Standort/*Very favourable site*				
Windmittel in Nabenhöhe/*Avarage wind speed in height of hub*	m/s	6	6,3	6,5
Spezifischer Stromertrag/*Specific electricity yield*	kWh/m² überstrichene Rotorfläche und Jahr *swept area and year*	500	555	575
Jahresstromproduktion/*Annual electricity output*	kWh/a	14 000	36 075	72 450
Spezifischer Investitionsbedarf/*Specific investment needs*	€/kWh • a	2,41	1,56	1,12
Stromgestehungskosten/*Electricity production costs*	ct/kWh	19,82	13,20	9,75
Guter Standort/*Favourable site*				
Windmittel in Nabenhöhe/*Avarage wind speed in height of hub*	m/s	5,5	5,8	5,9
Spezifischer Stromertrag/*Specific electricity yield*	kWh/m² überstrichene Rotorfläche und Jahr *swept area and year*	420	470	490
Jahresstromproduktion/*Annual electricity output*	kWh/a	11 760	30 550	61 740
Spezifischer Investitionsbedarf/*Specific investment needs*	€/kWh • a	2,87	1,84	1,32
Stromgestehungskosten/*Electricity production costs*	ct/kWh	23,60	15,59	11,44
Mittlerer Standort/*Avarage site*				
Windmittel in Nabenhöhe/*Avarage wind speed in height of hub*	m/s	5	5,3	5,4
Spezifischer Stromertrag/*Specific electricity yield*	kWh/m² überstrichene Rotorfläche und Jahr *swept area and year*	335	380	402
Jahresstromproduktion/*Annual electricity output*	kWh/a	9 380	24 700	50 652
Spezifischer Investitionsbedarf/*Specific investment needs*	€/kWh • a	3,60	2,28	1,60
Stromgestehungskosten/*Electricity production costs*	ct/kWh	29,58	19,28	13,94
Schwacher Standort/*Unfavourable site*				
Windmittel in Nabenhöhe/*Avarage wind speed in height of hub*	m/s	4,5	4,8	4,9
Spezifischer Stromertrag/*Specific electricity yield*	kWh/m² überstrichene Rotorfläche und Jahr *swept area and year*	260	300	320
Jahresstromproduktion/*Annual electricity output*	kWh/a	7 280	19 500	40 320
Spezifischer Investitionsbedarf/*Specific investment needs*	€/kWh • a	4,64	2,88	2,02
Stromgestehungskosten/*Electricity production costs*	ct/kWh	38,12	24,43	17,52
Sehr schwacher Standort/*Very unfavourable site*				
Windmittel in Nabenhöhe/*Avarage wind speed in height of hub*	m/s	4	4,2	4,3
Spezifischer Stromertrag/*Specific electricity yield*	kWh/m² überstrichene Rotorfläche und Jahr *swept area and year*	185	220	235
Jahresstromproduktion/*Annual electricity output*	kWh/a	5 180	14 300	29 610
Spezifischer Investitionsbedarf/*Specific investment needs*	€/kWh • a	6,52	3,93	2,74
Stromgestehungskosten/*Electricity production costs*	ct/kWh	53,57	33,31	23,85

* Nutzungsdauer 20 Jahre, 4 % Zinsansatz, Betriebskosten 55 €/kW Nennleistung.
Useful life 20 years, interest rate 4 %, operating costs 55 €/kW nominal power.

For the 7.5 kW plant, a positive working result cannot be achieved under the assumed conditions in the example.

Conclusions

In the examples presented here the electricity production costs in all cases are higher than the EEG payments for electricity fed into the network. For this reason a positive business result requires that a large production of the produced electricity must be used on the farm as substitute for bought-in electricity. So that this can be achieved, good planning, matching production with requirement, is needed. Where the electricity produced is only fed into the public network with an EEG payment of 8.93 c/kWh the result is not economically supportable. But as well as economic viability on given sites there are also questions of reducing CO_2 output in electricity production and of more independence from electricity price developments to be considered regarding decisions for and against a small wind turbine.

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Authors

Henning Eckel and **Stefan Hartmann** are members of the staff at the Association for Technology and Structures in Agriculture (KTBL e.V.), Bartningstraße 49, 67289 Darmstadt, e-mail: h.eckel@ktbl.de, s.hartmann@ktbl.de

Walter Eggersglüß is a staff member of the Schleswig-Holstein Chamber of Agriculture, Am Kamp 15–17, 24768 Rendsburg, e-mail: weggersgluess@lksh.de