Comparison of Energy Yield of Small Wind Turbines in Low Wind Speed Areas

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***Abstract*—The objective of this paper is to compare the energy yield and generated electricity cost of several commercially available small wind turbines under low wind speed condition. Many small wind turbines were not able to generate the amount of electricity promised by the manufacturers. The predicted annual energy yield simulated using manufacturers' power curve were sometimes higher than actual measured values by up to a factor of two. Furthermore, above a rotor size of 3 m, large diameter turbines performed better, having both low generated electricity cost (€/kWh) and high annual energy yield per swept area (kWh/m^2).**

***Index Terms*—Annual energy yield, cost analysis, low wind speed, power coefficient, small wind turbine, wind energy.**

Fig. 1. Photograph of several small wind turbines from different manufacturers at the Technopark Schoondijke (Netherlands) test facility. *Photograph by Jeroen Haringman (www.solarwebsite.nl).*

I. Introduction

THE global market for wind turbines has continued to grow in the past decade. On one hand, large utility scale wind turbines have over the years advanced to such an extent that the technology is substantially matured. The availability of research funding has led to continued improvements in large turbine systems. On the other hand, the technology for small wind turbines has not matured like its large-scale counterpart due to the nonexistence of such systematic research and development. According to [1], the global installed utility scale wind power was 197 GW at the end of 2010 (an increase of 24.1%) while the global market for small wind turbines (SWTs) grew by only 4% [2]. The report in [2] shows that in 2010 the units sold in the U.S. decreased by 20% although the market grew by 26%, indicating a shift towards larger grid-connected systems.

Two major reasons are identified as being responsible for the continued low penetration of small wind turbines [3]. They are the low energy yield and the cost of current standalone systems. Small wind turbines operate mostly in low and moderate wind speed areas, being sited where the energy is needed rather than where wind is best. Furthermore, many small wind turbines experience poor starting in low wind speeds which has a huge influence on energy yield [4], [5]. If the energy yield is low it may not be sufficient to meet demand and to make good return on investment. Fig. 1 depicts some small wind turbines installed in a test facility to measure the energy yield.

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Small wind turbines can be categorized into two types: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs), as shown in Figs. 2 and 3, respectively. There have been varying claims by both researchers and manufacturers about which turbine type is most attractive in terms of energy yield in low wind speed areas. Vertical axis turbines do not need to be pointed into the wind as they can access wind from all directions. However, the overall efficiency of the VAWT is not very impressive. Horizontal axis turbines have high overall efficiency compared with VAWT but they generally have difficulties operating near ground and in areas with turbulent winds because they require more laminar wind flows. In general, the efficiency of small wind turbines is low compared with large wind turbines [6], [7] which invariably leads to comparatively lower energy yield obtainable from SWTs. The low efficiency of SWTs is in part due to aerodynamics but also due to the lack of optimized designs [6].

The energy yield of the turbine can be increased by increasing its rotor diameter and hence rotor swept area. A study of some commercially available small wind turbines of 100- to 5000-W rated power shows that the trend in the variation of rated power is somewhat quadratic as the rotor diameter increases, as illustrated in Fig. 4. A cost comparison of the turbines also shows that there is a general trend of lower cost per swept area as the size of the turbine increases (increase in rotor diameter), as illustrated in Fig. 5. The cost per swept area is used rather than just the cost of the turbines or cost per rated power since the swept area gives a better indication of the total energy that can be generated by the turbine than the rated power given by the manufacturer.

The objective of this paper is to compare six commercially available small wind turbine systems, namely:

1) the 2.5-kW Turby;
2) the 5.8-kW Fortis Montana;

Fig. 2. Photograph of Fortis Montana, a horizontal axis turbine used at the Schoondijke small wind turbine test trials. Source: Provincie Zeeland.

Fig. 3. Photograph of Turby, a vertical axis turbine used at the Schoondijke small wind turbine test trials. Source: TU Delft.

3) the 1.4-kW Fortis Passaat;
4) the 1.5-kW Swift;
5) the 1-kW Zephyr Air Dolphin;
6) the 0.6-kW Ampair.

The comparison is based on their annual energy yield per swept area and cost per energy produced in a low wind speed climate. These parameters were used so as to provide a fair comparison since the turbines do not have the same diameter. The annual energy yield and cost are calculated for a given low wind speed climate and compared with measured values. This comparison and the methodology used to obtain the actual coefficient of performance are the original contributions of this paper.

This study is important because it has been reported that many small wind turbines are not able to deliver the energy predicted by the manufacturers [8], [9]. It, therefore, provides a means to verify product performance in terms of actual energy yield that small wind turbine can deliver.

The paper starts with a brief description of the six turbine systems and the resulting coefficient of performance based on manufacturers data. Modeling of the wind climate, annual energy yield, and actual coefficient of performance based on measured annual energy yield are presented next. The paper concludes with a comparison of the predicted and measured annual energy yield, and cost of generated electricity of the six turbine systems.

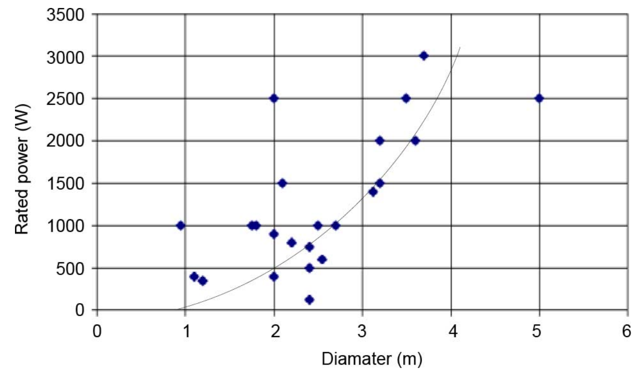


Fig. 4. Comparison of rated power as a function of rotor diameter.

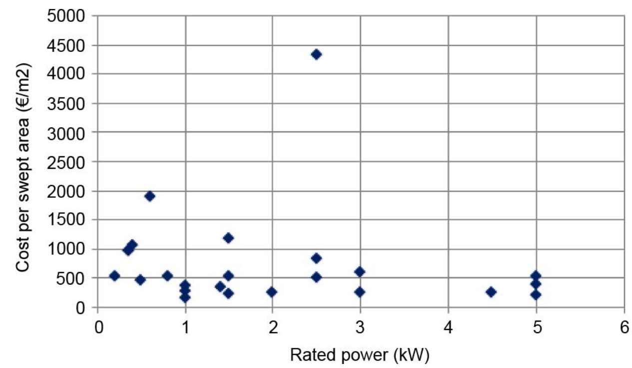


Fig. 5. Comparison of cost per swept area as a function of rated power.

II. Description of Investigated Systems

The investigated turbines were part of ten small wind turbines tested in a reasonably open field environment (there are some trees and buildings) at the Technopark test facility in Schoondijke (Netherlands). This test is a unique experiment, being probably the first time that several small wind turbines were tested at the same location and under the same wind conditions. The energy yield of the turbines was measured over a period of one year. Among the ten turbines installed at the Schoondijke, the results of six were used in this study. The turbines were selected based on available measured data which showed that in the first year these systems had no downtime. The investigated systems have different turbine specifications which makes for an interesting study.

Table I gives some technical specifications of the investigated turbines. Out of the six turbines, one is a VAWT while the rest are HAWTs.

Most systems investigated employ furling control by using a hinged tail vane to turn the rotor out of the wind when the wind speed is greater than the rated value and to realign it with the wind direction when the wind speed falls below rated value. At very high winds, the generator terminals are short-circuited to limit its rotational speed to as low value as possible. Furling control using a hinged tail vane is very popular among small wind turbines. Other types of speed regulation used includes

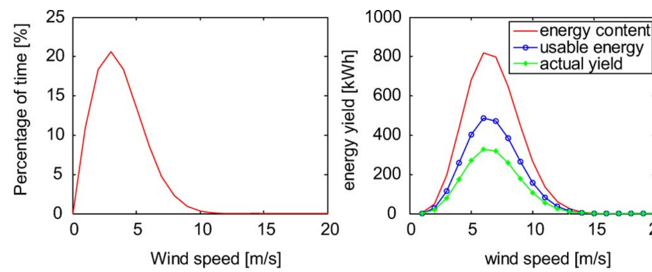
TABLE I
SPECIFICATIONS OF INVESTIGATED TURBINES[10]–[15]

	Fortis Mont.	Fortis Passat	Airdolphin	Ampair	Swift	Turby
Turbine type	HAWT	HAWT	HAWT	HAWT	HAWT	VAWT
Number of blades	3	3	3	3	5	3
Speed control	Furl	Furl	Stall	Pitch	Furl	none
Rotor diameter [m]	5	3.12	1.8	1.7	2.08	2
Swept area [m^2]	19.64	7.65	2.54	2.27	3.40	5.3
Rated power [kW]	5.8	1.4	1	0.6	1.5	2.5
Rated wind speed [m/s]	17	16	12.5	12.6	12	14
Cut-in wind speed [m/s]	2.5	3	2.5	3.6	3.4	4.0
Cut-out wind speed [m/s]	n/a	n/a	50	n/a	n/a	14
Output power [kW]*	4	1	1	0.6	1.5	1.6
Calculated Cp [%]*	18.9	12.1	36.4	24.5	40.9	28.5

*At wind speed of 12m/s

degrading the power coefficient to allow the blades to stall and using blade pitching weights mounted on the hub together with the blades.

There are no standards about what wind speed manufacturers should give the output power of their turbine (rated power). Many small wind turbine manufacturers usually give rated power at different wind speeds as indicated in Table I. Some manufacturers were able to profit from this lapse by showing "rated power" at high wind speed value to make it appear that their turbine has superior performance than their competitors. Therefore, the output power of each system has also been indicated at a common reference wind speed of 12 m/s by calculating the output power at this wind speed using manufacturer's power curve. Table I also gives the calculated coefficient of performance of the turbines at 12 m/s.



(a) (b)

Fig. 6. Weibull distribution of the wind (for an average wind of 3.7 m/s and k value of 2) and energy yield of a 3-m diameter turbine.

III. MODELING OF WIND DISTRIBUTION AND ENERGY YIELD

A. Wind Turbine and Wind Distribution

The energy yield from a turbine system is dependent on the wind speed and wind distribution of the site. The wind variation in most areas can be described by the Weibull distribution as shown in Fig. 6(a). It gives an indication of what percentage of time a certain wind speed occurs in a given site. The Weibull distribution is given by [16]

$$f(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} e^{-(v/a)^k} \tag{1}$$

where v is the wind speed and k is the shape parameter. The scale parameter a is used to scale the distribution for different wind speed regimes depending on the average wind speed (v_{av}). The average wind speed measured during the first year of the Schoondijke Field Test (3.7 m/s) is used for the wind distribution given in Fig. 6(a). The shape of the curve is determined by the shape parameter k which is assumed to be 2.

The available shaft power P can be expressed as a function of the wind speed as [16], [17]

$$P = \frac{1}{2}\rho_{\mathrm{air}} C_p(\lambda, \theta)\pi r^2 v^3 \tag{2}$$

where ρ_{air} is the mass density of air, r is the wind turbine rotor radius, v is the wind speed, and $C_p(\lambda, \theta)$ is the power coefficient or the aerodynamic efficiency, which is a function of the tip speed ration λ (tip speed divided by wind speed) and the pitch angle θ.

The output power produced by the turbine system will be less than this power due to losses in the generator and drive train. Fig. 6(b) shows the energy yield of a 3-m diameter turbine using the wind distribution of Fig. 6(a). It also depicts the energy content in the wind out of which about 59% may be captured by a wind turbine (usable energy) according to Betz Law. The actual energy yield of the turbine is less than this usable energy because in reality the efficiency of energy conversion by the turbine is less than 59% due to imperfections in blade manufacture which reduces the aerodynamic efficiency of the blades. In large wind turbines, due to the maturity of the technology used for blade manufacture, such imperfections are less which makes higher efficiency of conversion possible. The efficiency of conversion (coefficient of performance) of small wind turbines is usually less than 40% [6], [7].

Using the manufacturer's power curve and other characteristics presented in Table I, the coefficient of performance can be calculated as

$$C_p = \frac{2P}{\rho_{\mathrm{air}} A v^3} \tag{3}$$

where A is the rotor swept area, and ρ_{air} is the mass density of air, assumed to be 1.225 kg/m^3. Fig. 7 shows a plot of the turbines' calculated coefficient of performance as a function of wind speed based on specifications provided by the manufacturers.

Since most small wind turbines are not able to achieve a coefficient of performance of more than 40% (according to [7] small

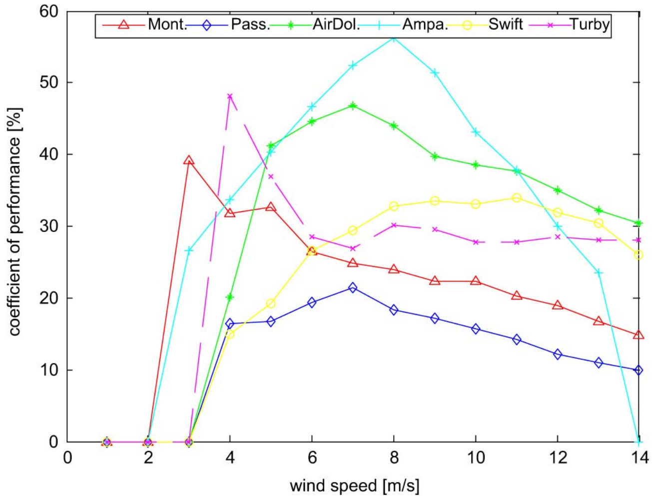


Fig. 7. Calculated coefficient of performance of the turbines versus wind speed based on manufacturers' specifications.

TABLE II
ANNUAL ENERGY YIELD AND COST OF THE TURBINES

Turbine	Cost [€]	Annual energy yield Calc. [kWh]	Field test [kWh]	Difference [%]
Fortis Montana	18,508	2804	2691	4.2
Fortis Passaat	9,239	674	578	16.6
Zephyr Airdolphin	17,548	516	393	31.3
Ampair	8,925	546	245	122.2
Swift	13,208	419	243	72.4
Turby	21,350	790	266	197.0

Coefficient of performance from measured annual energy yield	$C_{p(Meas.)}$ [%]
Fortis Montana	26.74
Fortis Passaat	14.75
Zephyr Air Dolphin	30.14
Ampair	21.06
Swift	13.95
Turby	9.79

wind turbines seldom deliver more than 30% of the energy in the wind over any significant period time), Fig. 7, therefore, suggests that some manufacturers may have indicated rather optimistic C_p values. This has some consequences in terms of the energy yield that the turbine is predicted to generate. As a result of this, it became necessary to find a good estimate of the turbine's coefficient of performance using measured data which can be used to predict the energy yield. This will be presented later in this section.

B. Annual Energy Yield

The amount of energy that can be captured by a wind turbine depends on the output power versus wind speed characteristics (power curve) of the turbine and the Weibull distribution of the site. The energy yield over a period of time T is given by [18]

$$E_y = T \int P(v) f(v) dv \tag{4}$$

where P is the generated power and $f(v)$ is the Weibull distribution given in (1). For a time period of 1 year, T is 8760 hours.

To predict the energy yield based on the manufacturer's power curve, the average wind speed measured in the first year of the Schoondijke Test Project is used with the Weibull distribution of the wind shown in Fig. 6(a). This gives the predicted annual energy yield ($E_{ay(calc)}$). The annual energy yield used in this work was measured at the Technopark Test Facility in Schoondijke where several small wind turbines were tested in an open field. The generated electricity during the first year of the Schoondijke Test Trials gives the measured annual energy yield in kWh/year ($E_{\mathrm{ay(meas)}}$).

C. Coefficient of Performance

It is useful to get an indication of the actual coefficient of performance of the turbines because of the reason given earlier. To do this, the measured annual energy yield of the turbines will be used rather than the power curve given by the manufacturers. The following approach is adopted. Again, the measured average wind speed is used to find the Weibull distribution of the wind $f(v)$. By combining (3) and (4), the annual energy yield can be written as

$$E_{\mathrm{ay}} = T \int f(v) \tfrac{1}{2} C_p \rho_{\mathrm{air}} A v^3 dv. \tag{5}$$

The annual energy yield from (5) should be equal to the measured annual energy yield. The coefficient of performance is then calculated as

$$C_{\mathrm{p(meas)}} = \frac{E_{\mathrm{ay(meas)}}}{T \int f(v) \frac{1}{2} \rho A v^3 dv}. \tag{6}$$

The energy yield of the turbine is simulated using the $C_{\mathrm{p(meas)}}$ values from (6) and the Weibull distribution of the site while the annual energy yield is also obtained by integrating the energy yield over the wind speed. It was observed that the annual energy yield obtained using this approach was the same as the measured annual energy yield from the site, thereby validating the adopted approach.

IV. Results, Comparison, and Discussion

Table II gives the result of the predicted annual energy yield of the turbines based on manufacturers' data and based on measured data from Schoondijke field test. Details of the field test measurement results can be found in [19] and [20]. The cost of the turbine systems presented in Table II were taken from system cost breakdown of the Project. The table also shows the coefficient of performance from measured annual energy yield ($C_{\mathrm{p(Meas.)}}$) according to (6), which gives an indication of the operating C_p of each turbine in Schoondijke during the first year of the project.

The results presented in Table II shows that none of the turbines were able to meet the energy yield promised by the manufacturers. In most turbines, large differences exist between measured and predicted annual energy yield, with only a few having differences that could be described as acceptable. This difference between calculated and measured annual energy yield was nearly 200% in one turbine. Compared with the coefficient of performance calculated using manufacturers' specifications, the values in Table II seem more like what we would expect from a typical small wind turbine operating in a low wind speed climate.

A. Annual Energy Yield

The coefficient of performance curves of the turbines were plotted in Fig. 7 using the manufacturers power curve. Comparison of the results in Fig. 7 and the differences between measured and calculated annual energy yield presented in Table II shows that most manufacturers whose C_p values were mostly below 30% had small differences in their annual energy yield.

According to Table II, the Fortis Montana and Fortis Passaat systems had the least difference in annual energy yields (4% and 17%, respectively). Their C_p values (Fig. 7) were mostly lower than 30% except at low wind speeds where turbine performance may be difficult to predict accurately.

The Ampair and Turby systems had the largest difference in annual energy yield (120% and 200%, respectively). The C_p values of the Ampair system were mostly above 30%. The Turby system, however, had fairly reasonable C_p values although this system had the highest difference in annual energy yield of almost 200%. It is possible that the Turby's performance is difficult to predict in low wind speeds due to poor starting, which could account for its low annual energy yield and large disparity between predicted and measured values.

Starting problems commonly occur in small wind turbines, especially at low wind speeds since they are self-starting. The cut-in wind speed of the Turby is 4 m/s, which is the highest cut-in wind speed amongst the six turbines (Table I). Bearing in mind that the measured average wind speed at the test site was 3.7 m/s, which is below the Turby's cut-in wind speed, it is possible that due to low wind speed conditions at the site, the Turby may have found it difficult to start. Even when the wind speed is higher than the turbine's cut-in wind speed, such wind speed needs to be sustained for a period of time before the turbine starts generating power [4], [5]. In low wind speed areas, this may not be the case as high gusts of short duration occur frequently rather than sustained high winds. Such wind condition where the average wind speed is below the Turby's cut-in wind speed may have led to a frequent *start–stop* condition with negative consequences on its energy yield.

The measured annual energy yield of the turbines is generally poor. The Fortis Montana system generated the highest annual energy yield of 2690 kWh/year which is less than about 3400 kWh/year consumed by an average Dutch household. However, in many developing countries, particularly in rural areas, electricity consumption is low. For instance, Nigeria's electricity consumption per capita in 2008 was only 140 kWh/year [21]. Electricity consumption per person in rural areas of Nigeria will be lower than this value. We estimate that less than 0.5 kWh per day or 180 kWh per year will be sufficient to meet the energy needs of a rural household. Based on this, electricity generation from the Fortis Montana system could provide the energy needs of up to 15 rural households.

B. Annual Energy Yield Per Swept Area

It is necessary to provide a fair comparison of the annual energy yield for all the turbines since they do not have the same rotor diameter. A useful figure of merit for the analysis of the turbine field performance is then the annual energy yield produced per rotor swept area. This is obtained by dividing the annual energy yield by the rotor swept area. Fig. 8 shows the annual yield per swept area based on measured field test and calculated values from manufacturers' power curve.

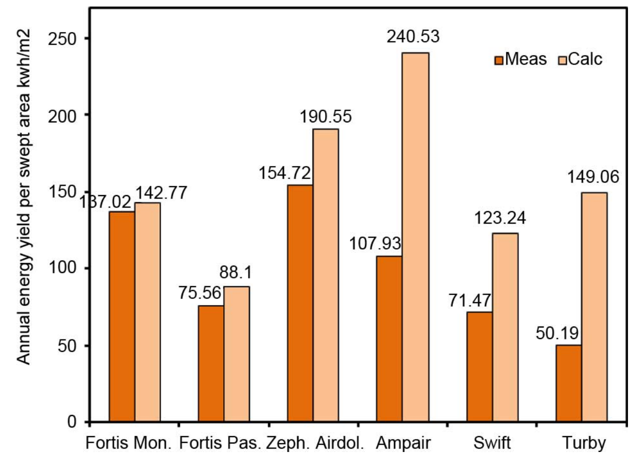


Fig. 8. Comparison of measured and calculated annual yield per rotor swept area of the systems.

The best performing turbine in terms of kWh generated per swept area is the Zephyr Air Dolphin system, generating more than 150 $\mathrm{kWh/m^2}$. The Swift system is the worst performing turbine generating about 70 $\mathrm{kWh/m^2}$. The Fortis Passaat system had the second highest annual energy yield of 578 kWh according to Table II. However, its electricity generation in terms of kWh produced per swept area is only 75 $\mathrm{kWh/m^2}$. The Passaat is a 3-m diameter turbine, yet its energy yield per rotor swept area is a factor of 2 lower than that of the Air Dolphin which is a 1.8-m diameter turbine. Therefore, the use of generated energy per swept area rather than just the generated energy is preferred in the comparison of energy yield of small wind turbines.

The annual energy yield per swept area has been plotted for different average wind speeds as shown in Fig. 9. It has been assumed that the sites have the same shape parameter value of $k = 2$. This plot was generated using the $C_{\mathrm{p(meas)}}$ values obtained from measured annual energy yield as explained in Section IV-A. It gives an indication of the annual energy yield each turbine is predicted to generate at other sites thereby providing a comparison of small wind turbine performance for different average wind speed conditions. It has been assumed that each turbine will operate at the same C_p as obtained from Section IV-A.

C. Cost Comparison

The actual cost of the turbine systems used in the Schoondijke Test Project are given in Table II. The cost of generated electricity can be estimated as the system cost divided by the total energy yield in the turbine's lifetime. In this paper, it was assumed that the turbines have a lifetime of at least 20 years and that during this lifetime they will operate with the same efficiency as during the test period. Additional cost for repair and maintenance have been neglected.

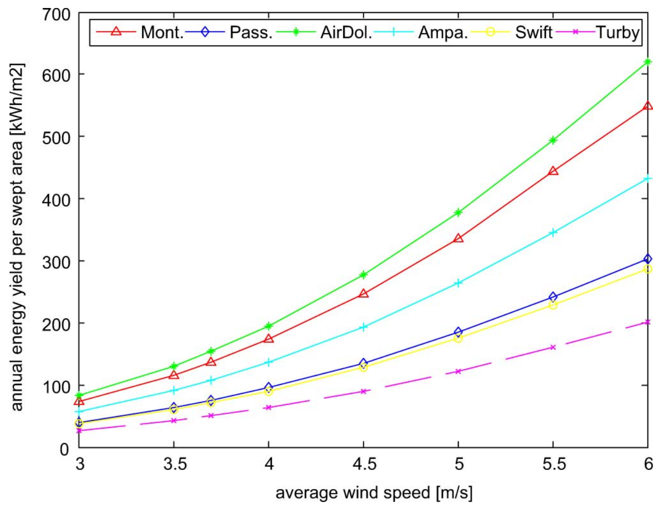


Fig. 9. Variation of annual yield per rotor swept area with annual average wind speed.

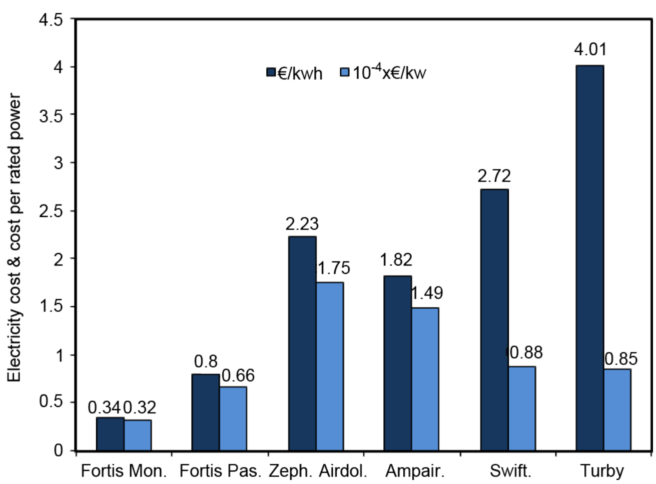


Fig. 10. Cost analysis of the turbines showing cost per rated power in euro per kW and cost of generated electricity in euro per kWh.

The cost of generated electricity in euro per kWh can then be calculated as

$$c = \frac{Ce}{T \times E_{\mathrm{ay(meas)}}} \tag{7}$$

where Ce is the actual system cost, T is the turbine's lifetime, and $E_{\mathrm{ay(meas)}}$ is the measured annual energy yield as indicated in Table II. A comparison of cost of generated electricity (€/kWh) is shown in Fig. 10. However, it must be pointed out that the lifetime of a small wind turbine depends partly on the design and manufacturing process. Furthermore, cost of repair and maintenance could become a major cost-determining factor over the turbine's lifetime.

In performing a cost efficiency analysis of the turbines, it is desirable to have systems with low €/kWh. Therefore, the most cost-efficient turbines according to Fig. 10 are the Fortis systems; their electricity generation costs were €0.34 per kWh and €0.8 per kWh for the Montana and Passaat systems, respectively. The least cost-efficient turbine is the Turby whose cost of electricity generation is about €4 per kWh. The graph should be viewed as indicative because in reality other variables which were not taken into account will come into play. For instance, some manufacturers may have paid extra attention to robustness in their design in order to achieve high reliability. Over the assumed lifetime of the turbines, maintenance cost and downtime would be low (compared with other systems) thereby increasing the competitiveness of such systems in terms of €/kWh.

Generally, the cost of the systems is considered high and perhaps even prohibitive especially for developing countries where small wind turbines are considered to have its greatest potential. The cost of generated electricity and cost per rated power of the most cost-effective turbine were €0.34/kWh and €3200/kW, compared with €0.05/kWh and €1300/kW [6] for large wind turbines.

Fig. 10 also shows the cost per rated power. It is common to use cost per rated power for the cost analysis of small wind turbines. However, since there is no universally accepted rated wind speed for which the rated power should be defined, a cost analysis based on this parameter could be misleading. The results of Fig. 10 shows that the cost per rated power of the Swift and Turby systems were less than the Air Dolphin and Ampair systems. However, the cost of generated electricity of the latter systems were actually lower than that of the former. This is partly due to the lack of a standardized wind speed value for the definition of the turbine's rated power. The large variation in the rated wind speed value of the turbines (see Table I) means that the specific parameters related to rated power cannot be compared, as they do not refer to the same conditions [6]. The cost of generated electricity (€/kWh) is a better figure of merit for performing cost analysis of small wind turbines.

Fig. 11 shows the variation of annual energy yield per swept area and cost per kWh produced with respect to turbine diameter. It has been claimed in [22] that the turbines that perform best are simply the largest ones. This suggests that turbines of higher diameter generally performed better than those with smaller diameter. The analysis in [22] was based on annual energy yield of the turbines instead of the annual energy yield per swept area. The plot of the annual energy yield per swept area and cost per kWh produced against the turbine diameter suggests that this claim may not be entirely correct.

With regards to cost per kWh produced, turbines of large diameter generally performed better having lower €/kWh than small diameter turbines. On the other hand, with regards to annual energy yield per rotor swept area, many small diameter turbines performed better than large diameter turbines. The Air Dolphin, which is a 1.8-m diameter turbine, generated twice the annual energy yield per rotor swept area of the Passaat system which is a 3-m diameter turbine. However, above turbine diameter of 3 m, large diameter turbines performed better, having both low €/kWh and high $\mathrm{kWh/m^2}$.

This study has shown that small wind turbines operate mostly under low wind speed conditions. This is evident by the measured average wind speed of 3.7 m/s and the inability of the turbines to meet the annual energy yield predicted by the manufacturers suggesting that many manufacturers may have indicated rather optimistic energy yield for their turbines. The difference between measured and predicted annual energy yield may have

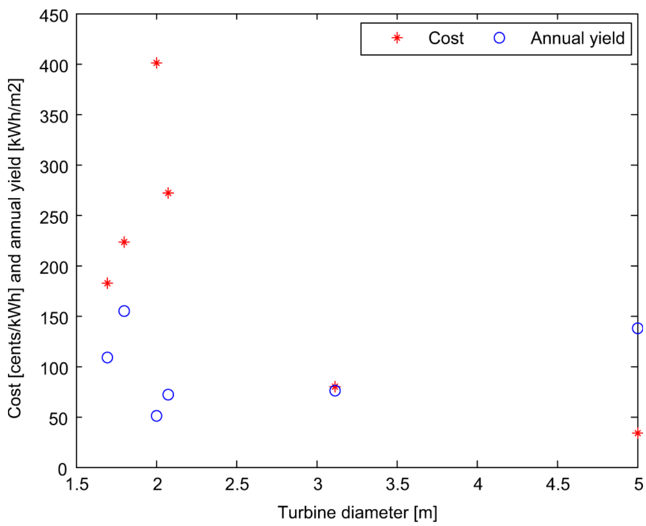


Fig. 11. Variation of annual energy yield and cost as a function of turbine diameter.

been as a result of the difference between the wind conditions in manufacturers' test facility and real-life test. This can be further illustrated by the high rated wind speed values used by manufacturers (e.g., 17 m/s for the Montana) which the turbine may never experience for a sustained period of time.

Furthermore, the turbines that performed well in terms of annual energy yield per rotor swept area (high $\mathrm{kWh/m^2}$) were those with low cut-in wind speeds, for instance, Air Dolphin (2.5 m/s) and Fortis Montana (2.5 m/s). Turbines with high cut-in wind speeds [for instance Turby (4 m/s) and Swift (3.4 m/s)] did not perform very well having low $\mathrm{kWh/m^2}$. It is possible that turbines with high cut-in wind speeds found it difficult to start under such low wind speed conditions which led to their low annual energy yield per swept area.

The inability of the turbines to deliver the energy yield predicted by the manufacturers also raises the issue of standards used in the SWT industry. The internationally accepted standards relevant to the SWT industry are the International Electrotechnical Commission (IEC 61400) standards, specifically the IEC 61400–2, IEC 61400–11, and IEC 61400–12 [6], [23]. However, they are not much used in practice [6], [23]. Furthermore, there was further uncertainty about exactly what should be measured and reported when conducting tests (power and acoustic) [23]. Such ambiguity and lack of proper standards is illustrated by the large differences between the performance predicted using manufacturers' data and that obtained through actual measurements. Such a consistent overestimation of the energy yield obtainable from the turbine is also an indication of the low maturity of the small wind turbine industry.

V. Conclusion

In this paper, we presented a comparison of the performance of six commercially available small wind turbine systems under low wind speed conditions. The annual energy yield predicted using the manufacturers' power curve was compared with measured annual energy yield from a field test. The actual coefficient of performance (C_p) of the turbines was determined using measured annual energy yield. The annual energy yield obtained using this C_p value is the same with actual measured value thereby validating the methodology adopted to obtain the C_p values. Since the turbines are of different sizes, the comparison was based on the annual energy yield per swept area $(\mathrm{kWh/m^2})$ and cost per generated electricity (€/kWh) in a low wind speed site.

Comparison of the annual energy yield showed that most systems failed to meet the performance stated by the manufacturers. In at least two systems, calculated annual energy yield was higher than measured values from field test by more than a factor of two.

Furthermore, large diameter turbines generally had lower cost per generated electricity than small diameter turbines. On the other hand, many small diameter turbines showed higher annual energy yield per rotor swept area than large diameter turbines. However, above the 3-m diameter, large diameter turbines performed better, having both low cost per kWh and high kWh per area.

The energy yield per unit area is indicative of the turbine's efficiency of energy conversion while the cost per generated electricity indicates the cost-effectiveness of the turbine. However, it has to be stated that in terms of overall performance of a turbine, the energy yield per swept area is less important than the cost of energy per kWh. As earlier stated, the energy yield of a turbine can be increased by increasing its rotor diameter which is a common practice when designing a wind turbine for low speed sites. In addition, the cost per generated electricity is usually the optimization criteria used by designers.

The paper, therefore, highlighted the need for manufacturers of small wind turbines to pay attention to low wind speed operation of their systems since small wind turbines operate mostly under such wind conditions. Low wind speed operation of small wind turbines has consequences in terms of the energy yield of the turbines due to difficulties in turbine starting. The higher the cut-in wind speeds, the more the effect of low wind speed operation on the annual energy yield. Turbines that performed well in terms of annual energy yield per rotor swept area (high $\mathrm{kWh/m^2}$) were mostly those with low cut-in wind speeds while turbines with high cut-in wind speeds did not perform very well.

The paper also highlighted another important issue regarding the need for better standardization of small wind turbine testing conditions such as rated wind speed, temperature, and pressure. The large differences between the performance predicted using manufacturers data and that obtained through actual measurements is an indication of the low maturity of the small wind turbine industry. Manufacturers should not just show power curves of their turbines but should also indicate whether the power curve was based on actual measurements or predicted using an assumed coefficient of performance. Such standardization should also include making sure that manufacturers indicate the test condition under which performance tests were carried out. This is necessary to ensure that users of small wind turbines buy products with confidence.

References

[1] Global Wind Energy Council, Global Wind Report: Annual Market Update 2010.
[2] American Wind Energy Association, U.S. Small Wind Turbine Market Report 2010.

[3] S. O. Ani, H. Polinder, and J. A. Ferreira, "Energy yield of two generator systems for small wind turbine application," in *Proc. IEMDC 2011*, Niagara, Canada, May 15–18, 2011.
[4] A. K. Wright and D. H. Wood, "The starting and low wind speed behaviour of a small horizontal axis wind turbine," *J. Wind Eng. Ind. Aerodynamics*, vol. 92, pp. 1265–1279, 2004.
[5] P. R. Ebert and D. H. Wood, "Observations of the starting behaviour of a small horizontal-axis wind turbine," *Renew. Energy*, vol. 12, no. 3, pp. 245–257, 1997.
[6] European Wind Energy Association, Wind Energy- the Facts: a Guide to the Technology, Economics and Future of Wind Power. London, Earthscan, 2009.
[7] P. Gipe, *Wind Power: Renewable Energy for Home, Farm, and Business*. Vermont: Chelsea Green Pub. Co., 2004, pp. 57–57.
[8] P. Gipe, Testing the Power Curves of Small Wind Turbines May 4, 2011 [Online]. Available: http://www.wind-works.org/articles/PowerCurves.html
[9] J. A. Stegmann and M. J. Kamper, "Economic and efficiency evaluation of different battery charging wind generator systems," in *Proc. 19th Southern African Univ. Power Engr. Conf.*, Johannesburg, pp. 205–210.
[10] Turby: the Wind Turbine for the Built-Up Environment May 4, 2011 [Online]. Available: www.turby.nl
[11] Fortis Technical Specification Sheet May 4, 2011 [Online]. Available: www.ason.ro
[12] Swift Turbines Technical Pack May 4, 2011 [Online]. Available: http://renewabledevices.com/rd-swift-turbines/
[13] Ultra-light Next-Generation Small Wind Turbine May 4, 2011 [Online]. Available: http://www.energyconnectuk.com/zephyr.html
[14] Zephyr Corporation Products May 4, 2011 [Online]. Available: http://www.zephyreco.co.jp/en/products
[15] Ampair 600 Wind Turbine, Operation, Installation & Maintenance Manual.
[16] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application*. Chichester, England: Wiley, 2002.
[17] H. Polinder, F. F. A. van der Pijl, G.-J. de Vilder, and P. J. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines," *IEEE Trans. Energy Convers.*, vol. 21, no. 3, pp. 725–733, Sep. 2006.
[18] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*. Chichester: Wiley, 2001, pp. 188–188.
[19] Schoondijke Field Test Result May 4, 2011 [Online]. Available: http://provincie.zeeland.nl/milieu_natuur/windenergie/kleine_windturbines
[20] S. Mertens, Schoondijke Evaluation Report May 2009.
[21] International Energy Agency, Electricity/Heat in Nigeria in 2009 May 4, 2011 [Online]. Available: http://www.iea.org/stats/
[22] K. de Decker, Real-World Tests of Small Wind Turbines in Netherlands and the U.K. The Oil Drum, Sep. 2010.
[23] D. Sharman, Getting Real About Small Wind Turbines (Part 2) Renewable Energy Focus Jan./Feb. 2010 [Online]. Available: www.renewableenergyfocus.com.

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