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ECONOMIC ANALYSIS OF SMALL WIND TURBINES

The market of small wind turbines is analysed from the economic point of view. The analysis judges investments in small wind turbine power plants on the basis of different economic indicators, such as Simple Payback (SPB), Net Profit Value (NPV) and Internal Rate of Return (IRR). Turbines from European and Polish markets were considered as the rated power of up to 10 kW was established to be the main criterion for that selection. Calculations of the tip-speed ratio and the power coefficient based on the wind resource reference data were conducted. On the basis of those considerations, an economic effectiveness study was performed via an estimated profit income from the turbine purchase. The model was further used to determine costs of a small wind turbine power plant that could compete on the current prosumer market dominated by photovoltaic and solar panels.

1. INTRODUCTION

In one of the previous papers [1], we focused on improvement in performance of one of small wind turbines available on the Polish market. Alongside efficiency, the modifications led to an increase in the profit margin from a feed-in tariff. Although a new look on small wind turbines was given, the study lacked a detailed impact on the real money value over the investment time as well as information about the turbine performance decay due to the machine ageing and wear. To overcome this deficiency, in a new study we analysed over 30 small wind turbines available in the European Union, each with a nominal power of up to 10 kW, on the target market sector of micro to small wind-based power plants [2]. To compare all the machines, the following steps were performed:

- calculations of the turbine power coefficient and the tip-speed ratio under nominal conditions,
- estimation of the annual energy production (AEP) for each turbine based on a location in the Lodz metropolitan area,
- energy-based cost calculations for selected wind power plants.

In Table 1, values of the power coefficients C_p

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$$C_p = \frac{2P_{rated}}{\rho v^3 \pi R^2} \tag{1}$$

and the tip-speed ratios (TSR) λ

$$\lambda = \frac{\Omega R}{v} \tag{2}$$

for each turbine under analysis can be found, where: v - rated wind speed, P - rated power, ρ - air density, R - rotor radius, Ω - nominal rotational speed.

The devices were divided into three groups, namely: vertical axis wind turbines (VAWT), horizontal axis wind turbines (HAWT), and diffuser augmented wind turbines (DAWT). In the third column, the number of blades is stated, while the product official name with its nominal power in kW is given in the fourth column. The columns 'C_p' and 'tip speed ratio' present the results of calculations based on the rotor geometry, rated power and rotational speed (rpm) as well as the rated wind speed obtained from a number of sources [2-8]. Dry air at the ambient temperature of 293 K and pressure equal to 101 325 Pa was considered. The data in the AEP column are used in an economic analysis to be presented later. The last column provides information on the turbine effective rated power per unit of the rotor swept area or the largest cross-section in the case of DAWT.

The obtained data were plotted in Fig. 1 to compare the performance among the competing designs and to theoretical turbine characteristics [9]. The outcomes were judged in respective categories in order to choose a versatile set of machines for economic studies. Winddam 2 kW (4V), Winddam 4 kW (9V), Aerocopter 2.4 kW (12V), Ecofys (7V) and Turby 2.5 kW (5V) are the most efficient VAWT. The first two turbines are produced in the United Kingdom and are examples of a modified H-rotor, where a set of inlet stators is used to control and accelerate the wind at induction. This is a primary reason for unusually high power coefficients for both Winddam versions. Aerocopter is a modified Darrieus-type turbine distributed in Poland and claimed to start at the cut-in speed of 1.5 m/s. For this optimized rotor, the manufacturer provides two power curves: the minimum and maximum one, producing either 2 or 2.4 kW of the rated power, respectively. We assumed the lower rated power for estimation of C_p as the turbine surpassed the Betz limit at the maximum power curve, suggesting thus that the characteristics had been altered. The Ecofys' Neoga adds skewness of the blades to limit losses, whereas its design consists of a Darrieus-type turbine combined with Savonius blades for the start-up. The Turby turbine, produced in the Netherlands, as a modified Darrieus turbine, uses blade sweep to derive more lift and ensure a low noise level at the rated tip speed ratio. Overall, the computed peak C_p values at the rated TSRs correspond well to the literature data, where VAWT designs are known to operate at lower efficiencies and at lower rotational speeds than the horizontal axis ones.

Among HAWT, a ducted SWT-3-mini (1DH), made in Poland on the U.S. license, reached one of the best performances. The 3-bladed WES Tulipo (10H) turbine actually attains the highest C_p value amid versions of the open rotor HAWT. Likewise, the optimal is the Polish Zefir (17H). Unlike before, the spread of data is broader here with some designs of unusually low efficiency. The optimal tip speed ratios do vary, but as the literature data show, are dominated by 3-bladed rotors.

Table 1. Characteristics of the selected turbines (input data from [2], Cp, TSR, AEP - own estimates)

Code	Type	Number of blades	Name and nominal power (in kW)	C_p	Tip speed ratio λ	AEP (in kWh)	Unit power * (W/m^2)
1V	VAWT	6	Venturi VAWT 0.5	0.150	2.72	74.75	489.7
2V	VAWT	2	Ropatec VAWT 0.75	0.198	1.96	227.3	327.1
3V	VAWT	2	Windside VAWT 1	0.071	1.16	376.4	250.0
4V	VAWT	5	Winddam DVAWT 2	0.375	1.21	787.5	390.6
5V	VAWT	3	Turby VAWT 2.5	0.264	2.98	440.1	471.7
6V	VAWT	6	WindWall VAWT 2.9	0.176	4.98	n/a	290.0
7V	VAWT	5	Ecofys VAWT 3	0.330	3.14	820.6	545.5
8V	VAWT	2	Ropatec VAWT 3	0.250	1.36	747.9	413.2
9V	VAWT	3	Winddam DVAWT 4	0.375	2.23	1185	390.6
10V	VAWT	2	Ropatec VAWT 6	0.250	1.36	1334	413.2
11V	VAWT	2	Windside VAWT 8	0.139	1.57	1130	666.7
12V	VAWT	3	Aerocopter 450 VAWT 2.4	0.313	0.94	548.2	245.6
1H	HAWT	5	Eclectic HAWT 0.4	0.171	4.32	205.9	421.1
2H	HAWT	2	Fortis Espada HAWT 0.8	0.127	8.22	358.3	210.5
3H	HAWT	3	Sviab HAWT 0.75	0.160	10.5	489.2	152.7
4H	HAWT	2	Travere HAWT 0.9	0.330	9.42	676.3	199.1
5H	HAWT	3	Fortis Passaat HAWT 1.4	0.074	7.91	577.4	183.0
6H	HAWT	2	Travere HAWT 1.6	0.330	10.1	1193	199.0
7H	HAWT	3	NHEOwind HAWT 2	0.312	2.14	n/a	322.6
8H	HAWT	2	Travere HAWT 2.1	0.241	17.3	3370	74.3
9H	HAWT	3	Tulipower HAWT 2.5	0.211	3.66	2815	127.6
10H	HAWT	3	WES Tulipo HAWT 2.5	0.344	4.31	2815	127.6
11H	HAWT	2	Travere HAWT 3	0.283	8.64	1511	294.7
12H	HAWT	3	Iskra HAWT 5	0.272	5.14	3816	218.3
13H	HAWT	2	Travere HAWT 5.5	0.323	7.54	4146	194.6
14H	HAWT	3	Fortis Montana HAWT 5.6	0.096	6.93	2296	285.7
15H	HAWT	3	Aircon HAWT 10	0.315	4.39	10389	252.5
16H	HAWT	3	Fortis Alize HAWT 10	0.250	9.16	4991	259.7
17H	HAWT	3	Zefir D7-P5-T10 HAWT 5	0.296	6.11	6214	181.9
1DH	DAWT	3-4	SWT-3-mini DAWT 3	0.338	3.53	1051	350.8*
2DH	DAWT	6-8	SWT-7-pro DAWT 7	0.265	5.34	3041	274.3**

* Unit power coefficient calculated from the nominal power divided by the swept area or ** by the largest cross-section area of the diffuser

In the next step, we used the manufacturer-provided power curves to estimate the amount of electrical energy produced by the turbines under consideration during one year of operation. An analysis was performed for the power curves up to 15 m/s. In the case of power plants where no data were provided up to this range, the values were copied. The results are based on the aggregated theoretical energy production obtained with the Weibull probability density function for local wind speeds. Due to diversity of designs, it was impossible to introduce a turbine capacity factor which would scale the turbine theoretical potential down to the realizable potential: an actual amount of electrical energy produced over time, which depends on meteorological conditions, the design of the energy conversion system and an authentic operational period. The wind data set for estimation of the theoretical AEP came from a meteorological station, located 10 m above the ground, located at the Lodz-Lublinek airport [10].

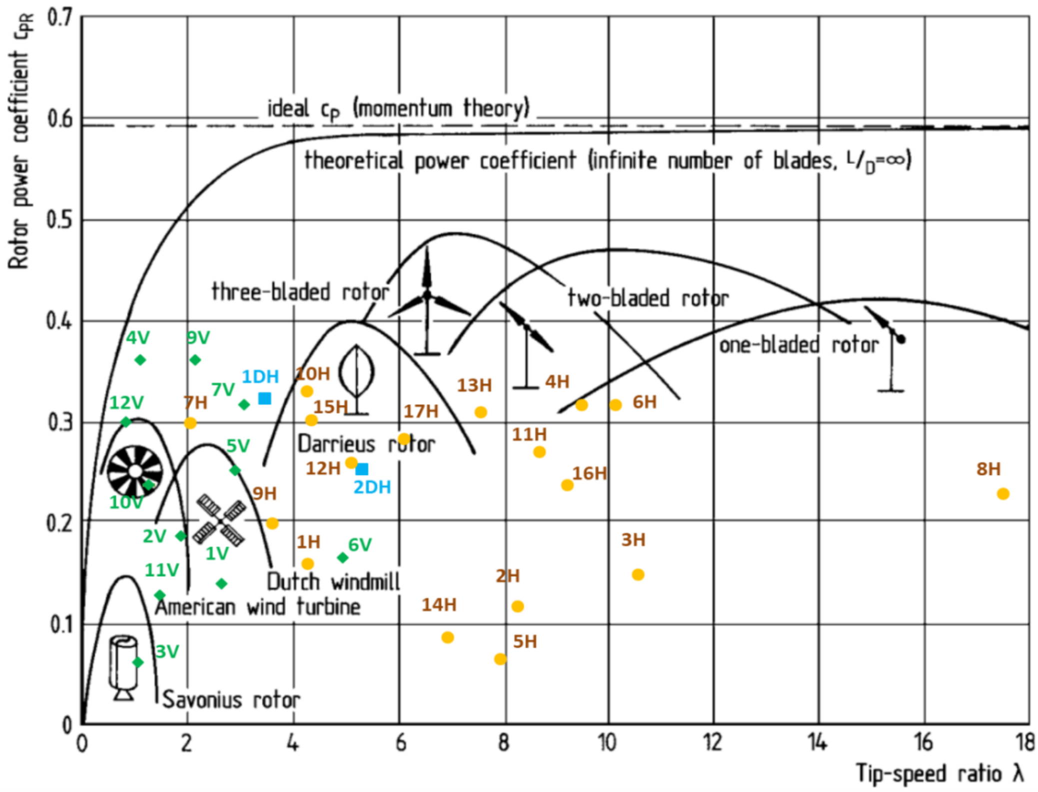


Fig. 1. C_p=f(*TSR*) graph for the analysed turbines (own estimates, the background picture from [9])

On the basis of the measurements conducted between 01/2010 and 09/2015, daily from 7am to 7pm, an averaged wind speed was equal to 3.6 m/s. The value was cross-checked against [11], where 3.4 m/s was reported. As a result, the arithmetic mean of 3.5 m/s was used. The data helped to draw a wind histogram, further approximated by the Weibull distribution function in Fig. 2:

$$f(v, A, k) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} * e^{-\left(\frac{v}{A}\right)^{k}} \tag{3}$$

where f (v, A, k) – wind speed probability, v – wind speed, A – scale parameter, k – shape coefficient. As a result, the following values were determined: $k = 2$ (therefore it is the Rayleigh distribution) and $A = 3.95$. Unfortunately, we were unable to compute the AEP for 6V (Windwall) and 7H (Nheowind) turbines because the manufacturer did not provide the power curve. A detailed economic analysis was conducted only for 10 selected turbines

(1DH, 2DH, 2H, 10H, 12H, 17H, 1V, 5V, 8V, 12V according to Table 1). They vary in design, price, performance and a country of origin, thus presenting a versatile set for comparison.

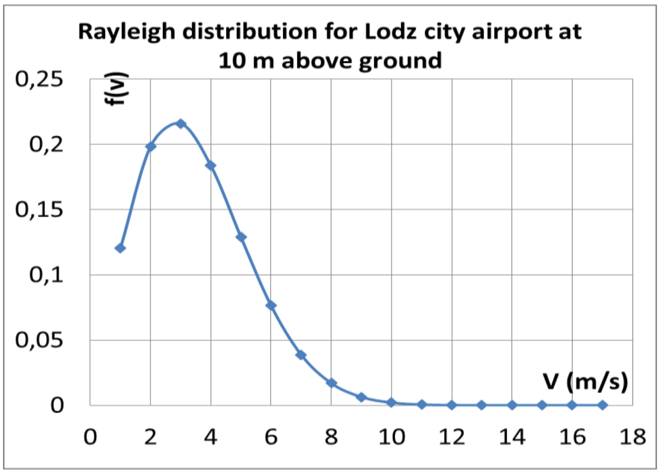


Fig. 2. Wind probability density function for the location under analysis

2. ECONOMIC PROFITABILITY CALCULATIONS

The analysis is conducted for the investment considered by a Polish energy consumer who wants to produce electricity from wind energy to supply own household. The consumer accepts initial costs connected to the purchase and installation of the turbine, but later, during its operation time, only inconsiderable repairs or an inverter replacement are permissible (the O&M costs are accumulated once over the entire period).

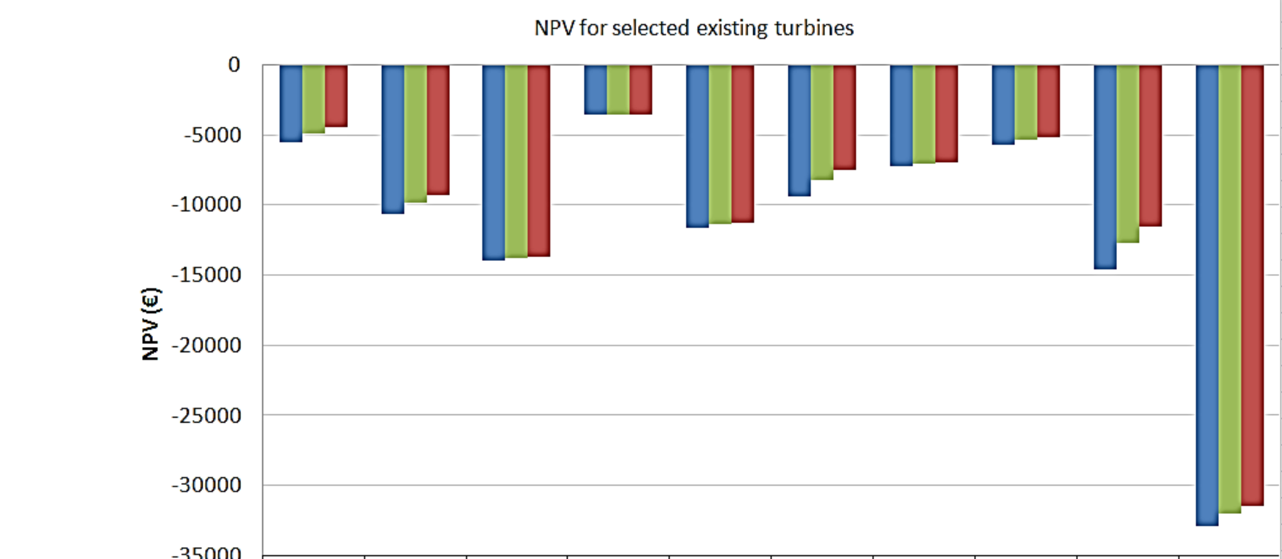
The detailed costs for each device are quoted in Table 2. Each retail price is expressed in €, basing on the average rate of exchange (1€ = 4.20 PLN) relevant as of November 2015, where appropriate. All prices of non-Polish wind turbines come from the report prepared by an international consortium [12]. Prices of wind turbines available in Poland come from the companies' websites or from direct contacts with their distributors.

Furthermore, the investment cost per kW of the turbine rated power is given. The capacity factor is calculated as a ratio of the amount of electricity produced (AEP) by a turbine and the amount of output that would be produced had it operated at the full nominal capacity for the entire period. This indicator immediately shows, for example, that despite bearing the lowest cost per kW, a Fortis Montana is 3-times less underloaded when compared to a much more expensive Zefir.

In the next step, a series of NPV calculations were carried out, where the cost of the electrical energy in Poland was required. Those data were taken from the Eurostat database: an average retail price of electrical energy in 2014 was 0.1408 €/kWh [13]. Investment horizons of 15, 18 and 20 years were considered, based on the turbine lifespan reported by most manufacturers to be between 15 to 20 years, on the condition that routine maintenance would be provided every six months. The results of the NPV analysis are presented in Fig. 3. The calculations are based on the 2% discount rate.

Table 2. Detailed investment costs for the selected turbines (input data from [12], capacity factor - own estimates)

	Fortis Montana	WES Tulipo	Turby	Energy Ball	Ropatec WRE030	Iskra	Aerocopter 450	SWT-3-mini	Zefir D7-P5-T10	SWT-7-pro
Nominal power	5.6 kW	2.5 kW	1.9 kW	0.5 kW	3 kW	5 kW	2.4 kW	3 kW	5 kW	7 kW
Country	Holland	Holland	Holland	Holland	Italy	UK	Poland	Poland	Poland	Poland
Investment (€)										
Turbine	7115	14950	11466	2479	10750	10150	7013	7140	23616	37800
Mast	1000	incl'd	1000	840	1000	4205	750	incl'd	1000	incl'd
Inverter	300	incl'd	incl'd	60	incl'd	300	incl'd	incl'd	incl'd	incl'd
Installation	624	500	675	200	595	500	300	300	500	500
Other	375	0	1300	75	345	800	0	0	590	0
Total (€)	9414	15450	14441	3654	12690	15955	8063	7440	25706	38300
O&M (€)	300	300	300	60	incl'd	300	150	150	150	150
IC (€)	9714	15750	14741	3714	12990	16255	8213	7590	25856	38450
IC per kW (€/kW)	1735	6300	7758	7428	4330	3251	3422	2530	5171	5493
Capacity factor	4.7%	12.9%	2.0%	1.7%	2.8%	8.7%	2.6%	4.0%	14.2%	5.0%



	Fortis Montana	WES Tulipo	Turby	Energy Ball	Ropatec WRE030	Iskra	Aerocop ter 450	SWT-3-mini	Zefir D7-P5-T10	SWT-7-pro
NPV (2% int. rate, 15 years)	-5560	-10658	-13945	-3579	-11637	-9350	-7222	-5688	-14614	-32949
NPV (2% int. rate, 18 years)	-4867	-9809	-13812	-3556	-11411	-8199	-7056	-5371	-12739	-32032
NPV (2% int. rate, 20 years)	-4428	-9270	-13728	-3542	-11268	-7468	-6951	-5170	-11550	-31450

Fig. 3. NPV values for the selected small wind power plants in the investment horizons under consideration

The net present value is in fact a profit calculation via a balance between incomes and costs incurred, with a possibility to account for the future value of money in the current analysis. This indicator is used in capital budgeting to analyse the profitability of a projected investment:

$$NPV = LS * NES * PVAF - IC \tag{4}$$

where: *LS* - lifespan (here understood as one of the investment horizons), *NES* - net annual energy savings, *PVAF* - present value annuity factor, or a quantity used to calculate the present value of a series of payments spread over time, *IC* - investment cost (as defined in Tab. 2).

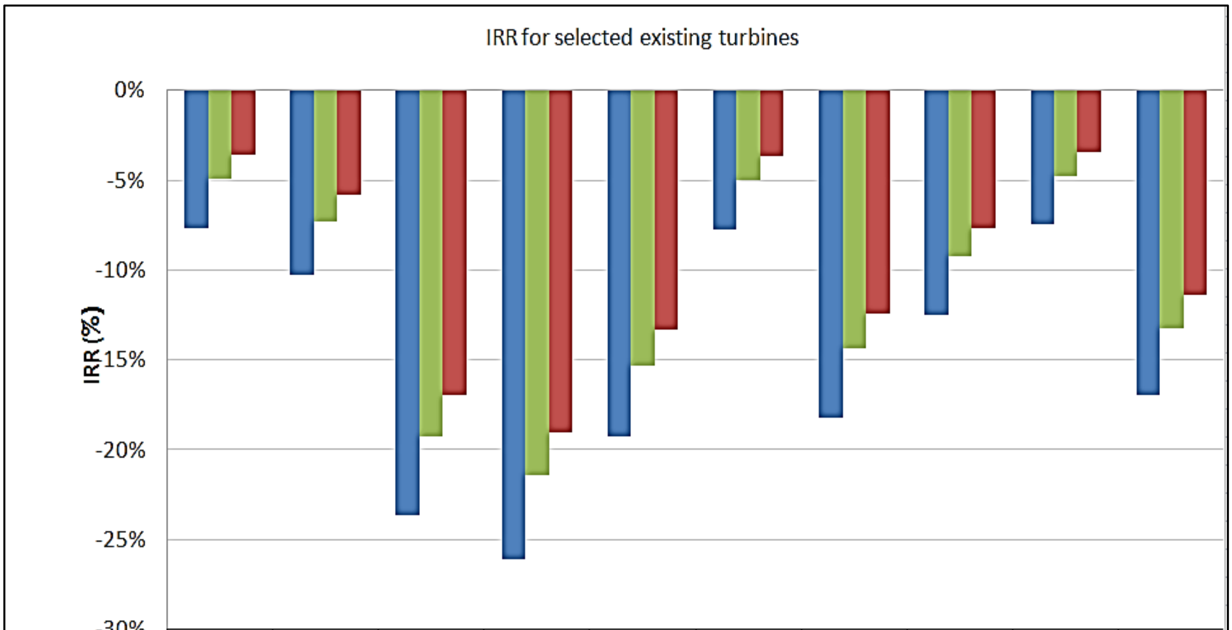
The *NES* identifies the amount of money per year saved due to a renewable energy system, which makes the purchase of grid electricity obsolete. The *PVAF* aggregates an overall expected impact of the investment, thus when it is higher, it elevates the incomes. Because being assessed over time, it needs an estimation of risk via a specified discount rate, or an interest rate by which the future value of money is projected onto the present times. Table 3 helps to understand an impact of the *LS* and the discount rate on the *PVAF*.

Table 3. *PFAV*s computed for the investment horizons under consideration

Interest rate	Investment horizon (years)		
	15	18	20
0.02	12.8493	14.992	16.3514
0.03	11.9379	13.7535	14.8775
0.04	11.1184	12.6593	13.5903
0.05	10.3797	11.6896	12.4622
0.06	9.71225	10.8276	11.4699

Due to the legislation adopted in the European Union, favouring RES (Renewable Energy Source), it is safe to assume a low interest rate, for example 2-4%, similar to government bonds that carry low risk. 2% that was used in our computations is the best case scenario yet as Fig. 3 shows that it does not secure a positive *NPV*. Interest rates higher than this would lower the *NPV* even more. None of the selected turbines will provide profit at the end of the considered timespans. The reader is advised that all values are based on the theoretical turbine potential so, in fact, are going to be lower than the presented ones even when one considers the household energy usage to be likely to increase annually. The figure confirms the current status of small wind turbines in Poland, a country where the small renewable energy market is dominated by solar and photovoltaic panels and where the number of turbine manufacturers is limited to barely a few.

Figure 4 shows an internal revenue rate estimation. The *IRR* is used in capital budgeting to measure the profitability of potential investments. It is a discount rate that would make the net present value (*NPV*) of all cash flows from a particular investment equal to zero. *IRR* calculations rely on the same formula as the *NPV* does. Thus, *IRR* results which are negative claim that the particular investment is not profitable in the assumed time. The plot shows that no single turbine produces a positive *IRR* value in the investment lasting up to 20 years. Despite the fact that the Energy Ball turbine had the highest *NPV* values, it turns out that its *IRR* is the lowest. It is the cheapest turbine, yet its nominal rated power is also minimal. Thus, all Net Energy Savings it returns are small if compared to other turbines. On the other hand, the Zefir turbine is actually able to provide the best return rates, despite yielding an unacceptable *NPV*. On this basis, it can be considered as conditionally profitable because its *IRR* may be approaching 0 with a slight increase in the turbine operation time (>20 years) or a possible increase in the electrical energy price in the future. The first option is not impossible: repowering a turbine (replacement of the rotor) is already a practice in the matured multi-megawatt turbine industry. Provided that some new cheaper technologies in the SWT market emerge, the same can be done for Zefir. A grid electricity price rise in the years to come could further increase net energy savings and reduce a negative impact of additional costs of repowering for this turbine.



	Fortis Montana	WES Tulipo	Turby	Energy Ball	Ropatec WRE030	Iskra	Aerocopter 450	SWT-3-mini	Zefir D7-P5-T10	SWT-7-pro
IRR (15 years)	-8%	-10%	-24%	-26%	-19%	-8%	-18%	-12%	-7%	-17%
IRR (18 years)	-5%	-7%	-19%	-21%	-15%	-5%	-14%	-9%	-5%	-13%
IRR (20 years)	-4%	-6%	-17%	-19%	-13%	-4%	-12%	-8%	-3%	-11%

Fig. 4. *IRR* values for the selected small wind power plants in the investment horizons under consideration

The direct cause for a large negative *NPV* at low *IRR* values is the Zefir's significant purchase cost despite its high capacity equal to 14.2% - a mark of a robust design. Figure 5 shows a power curve for this turbine compared to three other machines. The Zefir turbine reaches its nominal power at the lowest wind speed, thus maximizing its energy output for the given local wind climate. Two other turbines which can be considered are Fortis Montana and Iskra, but their *ROI*s (Return On Investments) would take even more time despite a low retail price. Interestingly enough, the most powerful turbine, SWT-7 pro, is not able to secure profit for given wind conditions as it reaches the nominal power at 12 m/s, above which, as the Weibull distribution shows, less than 0.01% of local wind energy resources are available.

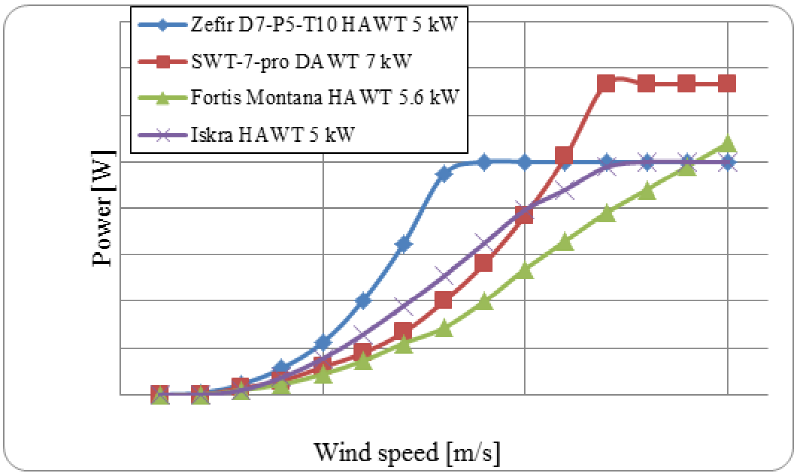


Fig. 5. Power curves for best performing HAWTs and the ducted turbine with the highest rated power

In general, at the moment, none of the turbines available on the Polish market are economically justifiable in the time horizons under analysis. If subsidies are introduced into the legislation, perhaps the Zefir turbine could be an asset. This is a good news since legislation changes and governmental support for SWTs are inevitable in order to bolster the COP21 ambitious plans to make SWTs an essential part of the energy mix.

Further on, we used the derived econometric model to compute a satisfactory retail price of the 3kW turbine that could provide a positive *ROI* at the end of its lifespan. Therefore, the Zefir D7-P5-T10 was chosen as the base design. For this single turbine, it is now possible to assume a capacity factor as a function of time (operational lifespan). This helps to derive a more realistic turbine total energy production, taking into consideration the machine wear and ageing. Unfortunately, the literature is scarce in terms of the information on the small wind turbine capacity factor evolution over time. Therefore, the capacity reported for multi-megawatt machines was used instead [14]. Figure 6 presents an estimated average capacity factor for large HAWT farms. In [14] the trend was termed as quadratic and derived from the operational data logged monthly for 832 Danish wind farms over a period of 16 years. We approximated the same data set by a linear trend with the *R2* coefficient equal to 0.99. This allowed one to progress the curve beyond 16 years up to 20 years, which is relevant for the current study. The data was next proportionally scaled by the capacity factor ratio of 0.142/0.217, comparing the initial capacities, which resulted in own estimate of the SWT capacity factor decay over the operational lifespan up to 2035.

The results of this statistical analysis demonstrate an undeniable and, statistically significant, decline in the operating performance of the wind turbine as it grows older. Next, we introduced four variants of a micro wind turbine with the rated power of 3 kW. Table 4 presents details of the cost scenarios, the total output energy based on own capacity factor model and average annual savings, mean prices of electricity produced by this power plant over 18 years and a unit price per kW.

We decided to assume the total investment costs (*IC*) of that "would-be" turbine between 3000 and 9000 €. Thus, the costs per kW at the most expensive option are somewhat between the cheapest (per kW) Fortis Montana turbine (1735 €/kW, see Table 2) and the robust Zefir turbine (5171 €/kW).

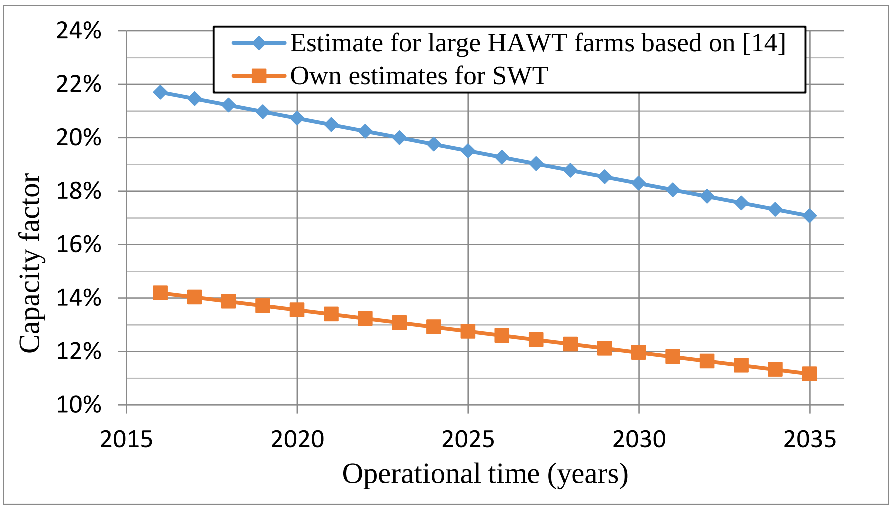


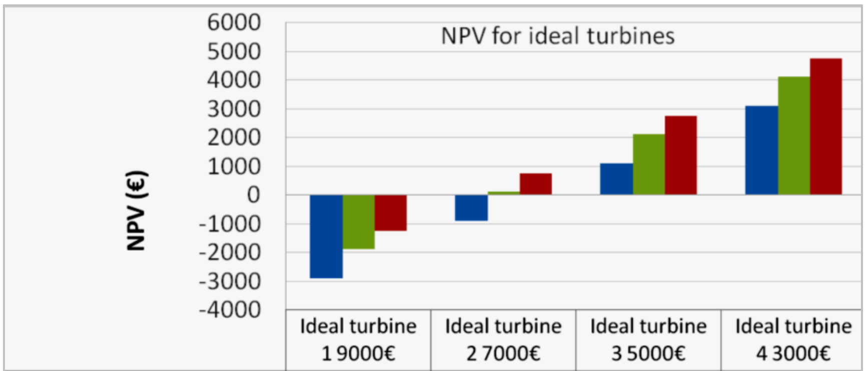
Fig. 6. Estimated decay in the turbine capacity versus time

Table 4. Economic analysis for the considered cost-optimized 3 kW turbines, data for 18 year-long investment

	Ideal turbine 1	Ideal turbine 2	Ideal turbine 3	Ideal turbine 4
Nominal capacity (kW)	3	3	3	3
Country of operation	Poland	Poland	Poland	Poland
IC (€)	9000	7000	5000	3000
Total output energy (kWh)	60710	60710	60710	60710
Avg. annual NES (€)	475	475	475	475
Avg. price per kWh (€/kWh)	0.1482	0.1153	0.0824	0.0494
IC per kW (€/kW)	3000	2333	1667	1000

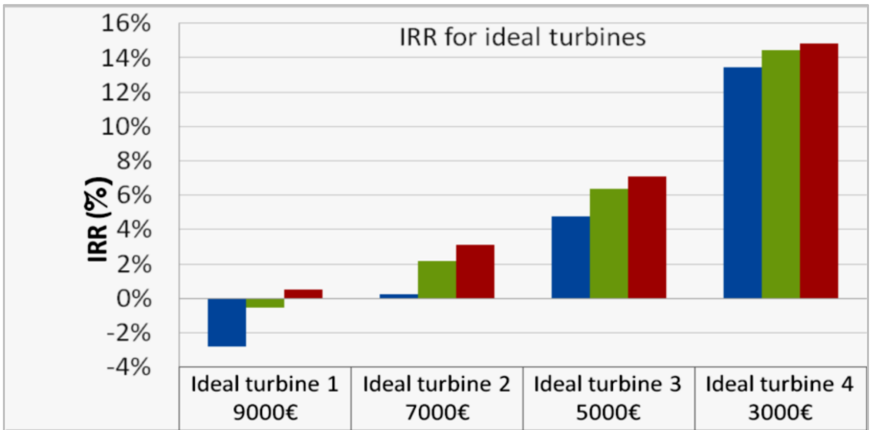
The cheaper variants of the ideal turbine from Table 4 are gradually decreasing the average price per kWh, thus creating a variant with a unit cost of 1667 €/kW, comparable to the aforementioned Fortis Montana. Hence, only Ideal turbine 4 seems to be beyond the current price trend. In this sense, the average electricity cost is also spread from a value comparable to contemporary grid electricity charge down to a really attractive 5 cents per kWh, a value so far achieved by large wind farms co-financed by governmental subsidies.

The model was then used to assess the *NPV* and *IRR* in the considered machine lifetime scenarios of 15, 18 and 20 years. Figures 7 and 8 present these results. From the analysis, it stems that only Ideal turbine 3 and 4 are profitable and achieve positive rates of return for all the investment horizons. However, given the model assumptions, where turbine energy output was not treated for availability (for large wind farms it reaches 95%, whereas there is not enough data for SWT to determine a similar figure), a low risk discount rate for the *NPV* analysis and a steady wind model free of turbulence and shear influence, Ideal turbine 3 should be treated as conditionally profitable.



	Ideal turbine 1 9000€	Ideal turbine 2 7000€	Ideal turbine 3 5000€	Ideal turbine 4 3000€
NPV (2% int. rate, 15 years)	-2898	-898	1102	3102
NPV (2% int. rate, 18 years)	-1881	119	2119	4119
NPV (2% int. rate, 20 years)	-1235	765	2765	4765

Fig. 7. *NPV* values for the virtual small wind power plant in the investment horizons under consideration



	Ideal turbine 1 9000€	Ideal turbine 2 7000€	Ideal turbine 3 5000€	Ideal turbine 4 3000€
IRR (15 years)	-3%	0%	5%	13%
IRR (18 years)	-1%	2%	6%	14%
IRR (20 years)	1%	3%	7%	15%

Fig. 8. *IRR* values for the virtual small wind power plant in the investment horizons under consideration

In other words, a turbine with a unit price as Fortis Montana and optimized for low speed conditions as Zefir is likely to guarantee the profit under favourable circumstances. Only Ideal turbine 4 might be considered unconditionally profitable. Its payback time (the number of years it takes for the energy savings to offset the initial investment) amounts to little more than 6 years. Furthermore, it possesses a high interest rate and can secure the net profit of over 3000 €, a value equal to its purchase price, at the end of the 15-year-long investment.

3. SUMMARY

To ensure the maximum profit, the *NPV* should be higher than zero and higher than the *NPV*s of other competing projects. None of the analysed investments fulfils this basic criterion. This effect can be technically leveraged by increasing grid energy prices in the time horizons under analysis. In the calculations presented herein, this was not taken into account, thus a rather conservative look onto the issue is presented. The *IRR* simulations have proven to lead to similar conclusions. Due to such a turn of events, the econometric model was employed to derive a small turbine total investment cost that could return the profit to a Polish investor interested in supplying energy to own household. The study showed that to be economically justifiable, a realistic cost of the SWT should not exceed 3000 €, given the realizable potential of the machine. Furthermore, the rotor has to be optimized for low speed conditions via reduction of the blade mass and by ensuring the rotation with an acceptable tip speed ratio to minimise noise. Only then it will be competitive on the market in comparison to other RES technologies and can truly turn the market orientation towards wind turbines as a viable alternative for energy prosumers. At the same time, such a price would make the energy- and cost-optimized turbine extremely competitive on the wider European market, in the light of the comparison to other turbines presented herein.

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