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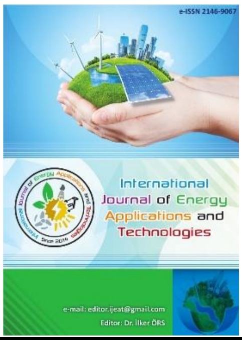

Original Research Article

A case study: Small scale wind turbine system selection and economic viability

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ABSTRACT

Increasing electricity production costs coupled with rising energy prices drive people to become energy independent. Wind energy systems can be one of the most cost-effective home-based renewable energy systems. A small-scale wind turbine can reduce the electricity bill slightly or up to 100% depending on the quality of wind resource of the site. More people across the world are seeking a solution against increasing electricity rates and a way to harvest their local wind resources. The aim of the study is to analyse an economic viability of a small-scale wind turbine system for residential use in southern Turkey. For this objective, firstly, an actual onsite wind data is evaluated. Five different on-grid small-scale wind energy production system alternatives which required to meet the electricity demand are offered. Performance of each turbine are examined; cost and benefit analysis based on cash flow, net present value, levelised cost of energy and payback periods are calculated. Recommendations are provided to the investor to make a decision on the optimum wind turbine selection based on performance and economic viability for the given site. At last, an overview of what is feasible on the preferred site is presented.

Keywords: Small-scale wind turbines, Wind energy economics, Turbine selection

1. Introduction

According to Global Wind Energy Council numbers [1], global wind power capacity in large-scale wind turbines has increased at a compound annual growth rate (CAGR) of 21% from 24 GW in 2001 to 540 GW in 2017. In 2017, $ 107.2 billion invested which makes the wind sector one of the fastest growing industry in the world. In the same year, Turkey added 766 MW to its installed capacity and reached up to 6.85 GW in total by the end of 2017, that makes the country the sixth in EU.

Not only the market for global large-scale wind turbine but also the global small-scale wind turbine market has also expanded due to the increasing energy demand. Small-scale wind turbine is defined as wind-powered electric generator with a rated capacity less than 50 kW, generally intended to supply electricity for residential use and/or small farms [2]. The motivation for installing a small-scale wind turbine varies; to be in control and independent in terms of energy, going for an eco-friendly and sustainable life, more affordable access to electrical energy, and so on. A small-scale wind turbine produce electricity more costly than a large-scale wind turbine especially in poor wind sites [3]. Therefore, strong growth has been expected for the small-scale wind market, and it is anticipated to value over $ 1.79 billion at a CAGR of 14.3% by 2025 [4]. Presently, Europe is the global leader of the small-scale wind market with about 42% of the total capacity. While Germany and UK hold the maximum of share, growing awareness in Turkey is anticipated to drive small-scale wind turbine industry growth, as energy demand and electricity prices continue to rise.

The purpose of this study is to assess the potential of small-scale wind turbines in terms of feasibility and effectiveness. A resident located in a rural area in the south of Turkey is evaluated for installation of a small-scale wind turbine. Like the global trend in energy costs, electricity prices in Turkey gradually increase. So, rising and unpredictable costs of energy drive residents a desire to use free electricity and become personally energy independent.

In order to achieve the aim of this study, it is structured in 4 sections. Section 2 introduces an overview of methodology that covers Turkey's electricity market, wind resource analysis of the site and distributed wind energy generation, turbine choices based on the investor's needs, energy calculations for each turbine, and economic indicators of them. Section 3 gives the results of cost and benefit analysis, while section 4 presents the final conclusion, and recommendations for the investor.

2. Methodology

2.1. Turkish electricity market framework and residential demand

According to Turkish Energy Market Regulatory Authority (EPDK), between 2000 and 2017, total electricity consumption of Turkey increased from 128 TWh to 286 TWh, and it is projected to be risen by 175% and reach up to 500 TWh by 2023 with current policies. In parallel to this trend, residential use also increased that accounts for nearly one quarter of the entire electricity consumption. Figure 1 shows the seasonal changes of consumption for the last two years [5].

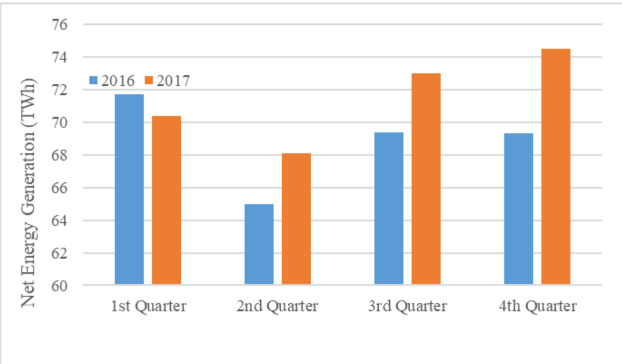

Figure 1. Change in quarterly electricity consumption in Turkey

Electricity is used for several purposes from lightening to heating/cooling in residential areas. There are several impacts that effects the energy consumption like the household size, the income, the climate in the region, and so on. So, each house has its own factors that determine the energy consumption. Therefore, instead of considering the national average residential electricity consumption per household, this paper established on actual energy budget of the investor. Based on the investor's electric bills from last year; the minimum demand per day was 9 kWh, while the maximum energy demand was 13.5 kWh. Therefore, the annual onsite energy demand will most likely be between 4000 kWh and 4200 kWh per year.

2.2. Site characteristics

The annual energy output for a typical small-scale wind system is calculated with the annual energy production (AEP) model which is given in section 2.4. This model estimates the annual energy production according to the wind speed probability. Therefore, wind resource in the given area is evaluated in this section.

The considered place is a rural property. The site has an elevation of approximately 2 meters above sea level. Its surface is flat and small bushes are planted along the boundary. The site is connected to the local grid.

The wind data used in this case was collected over one year from an onsite 10m mast which is considered by many manufacturers as a minimum height for good quality wind source to generate electricity with wind turbines [6]. Then, actual measurement of the wind resource was analyzed.

Table 1 Summary of measurements of wind data at 10m mast

Total wind speed data (hourly)	8760
Number of wind speed data over 3.5m/s	6642
Annual average wind speed	5.23 m/s
Average power density	0.157 kW/m^2
Prevailing wind directions	E, W and SW
Strongest prevailing winds	W and SW
Calm winds (<3m/s)	%16.22
Strong winds (>8m/s)	%12.13
Weibull shape parameter	2.167
Weibull scale parameter	5.889

Smooth surrounding environment, low population and low density of dwelling are the advantages of the site since these factors lead a stable and even wind flow [7].

Figure 2. Windrose diagram at the location

Windrose diagrams show the predominant wind directions in a specific location, and tell if the wind is strong enough to produce the expected energy. They are used in order to determine the orientation of the wind turbines [8]. In Figure 2, the windrose diagram for our case is given; according to calculations 25%, 19%, %14 of the time wind blows from east, west, southwest respectively. Also, west, southwest and west winds carry the strongest winds.

The site's wind speed distribution is necessary for the calculation of the performance of a wind turbine [9]. In Figure 3, the wind distribution is given. Simply this graphic aims to show the occurrence of wind speeds over a year and it shows at which speeds the wind blows most over a year. Generally, cut-in wind speeds for small-scale wind turbines are around 3.5 m/s, and in our case 75.8% of all times the wind speed is over the cut-in speed.

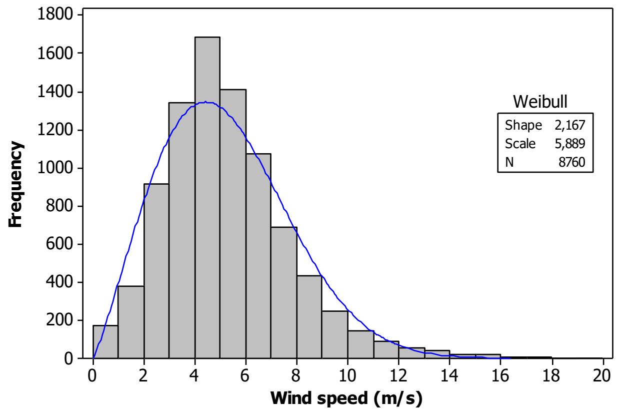

Figure 3. Wind speed distribution

The behavior of the wind speed is generally characterized with a Weibull distribution [10]. The probability density function is defined by the parameters of scale (c), which is related to the average wind speed, and shape factor (K), which indicates how pointed the distribution is. In this case, the wind data fitted to a Weibull density function and the shape and scale parameters are found 2.167 and 5.889, respectively.

2.3. Small-scale wind turbine choices

The turbines that are listed as candidates were chosen based on rated capacity and the availability on the market. Investor requested a horizontal wind turbine since they emerged as the dominant type. In Turkey, the cost of a standalone system (off-grid) installation is higher comparing to a grid-connection, so the nearest local grid will be used in this case. Also by this way, electricity can be provided from the supplier during periods of slow wind speeds and/or high energy demand. According to local grid connection regulations in Turkey, all costs incurred from the connection to the local network borne by the investor. Legal aspects of small-scale wind turbines in Turkey will not be discussed any further in this paper.

Five types of small-scale wind turbines are examined; all has different rated capacity from 600W to 3kW. Several scenarios are created, such as installing 4 turbines of 600W Proven and 2 turbines of 1kW Bergey. However, pairing two different types of turbines are not considered. Table 2 shows an overview of the wind turbines that are evaluated in this paper. All technical specifications regarding wind turbines are obtained from the manufacturer's data [11–14].

The prices *(in USD$)* reflect the actual market prices from several suppliers, and includes 10m tower and turbine only. 10m mast is chosen by the investor in order to eliminate high aerodynamic noise levels generated by the wind turbines. For any additional costs like freight, foundation costs etc. are not included. However, for the installation cost calculations 70% of wind turbine costs will be added since all the works will be carried out by a contractor. This percentage is approximated from the price quotes that the investor had collected already.

Table 2. Evaluated small-scale wind turbines

	Proven WT600	**Bergey 1kW**	**Proven WT2500**	**Skystream 2.4**	**Whisper500**
Rated Capacity (kW)	0.6 kW (0.6 kW x 4)	1 kW (1 kW x 2)	2.5 kW	2.4 kW	3 kW
Rotor Diameter (m)	2.55	2.50	3.50	3.72	4.50
Hub Height (m)	10	10	10	10	10
Swept Area (m^2)	5.10	4.91	9.62	10.86	15.89
Cost (each)	$1,000	$1,600	$3,500	$3,300	$4,100

2.4. Energy calculations

The available power from the wind is proportional to the cube of the wind speed and the expected power for a given wind speed *u* is in Equation 1;

$$P_{wind} = \frac{1}{2}\rho\pi r_r{}^2u^3 \qquad (1)$$

where ρ is the air density (kg/m^3), r_r is the rotor radius, and $\pi r_r{}^2$ indicates the rotor swept area. For the calculation of power production of a wind turbine is in Equation 2;

$$P_{turbine} = P_{wind} \times C_p \qquad (2)$$

where C_p is the capacity factor that stands for a fraction of available power in the wind that captured by the turbine. Manufacturer's power curves [11-14] are used for obtaining capacity factor values. A power curve shows the turbine's power production at various wind speeds. Figure 4 shows all the wind turbines' power curves.

Expected energy at a specific wind is the multiplication of $P_{turbine}$ and the number of hours of a relevant speed. In this case we have considered the annual energy production (AEP) and utilize Equation 3;

$$AEP = \sum_1^u E(P_{turbine})_u \qquad (3)$$

Table 3 shows the AEP calculations for all five different wind turbines. Since the investor's electricity demand is calculated between 4000-4200 kW/year, three out of five system alternatives are capable of meeting the on-site electricity demand.

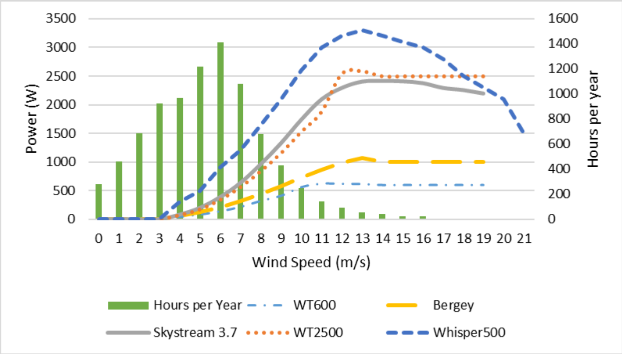

Figure 3. All five wind turbines power curves and the site's wind speed distribution

2.5. Economic aspects

A small-scale wind turbine system is capital intensive. The capital costs *(including wind turbine, grid connection, licensing procedures, permits, and monitoring systems)* can be as much as 75% - 80% of the total cost of the wind project over its entire lifetime [15]. Other costs are mainly operating and maintenance costs.

In this case Payback Period (PP), Net Present Value (NPV) and Levelised Cost of Energy (LCOE) and are analyzed.

Payback Period (PP) helps to determine the number of years taken by the wind turbine investment to recover the initial investment costs. The aim is to find out how long it will take to pay back the investment.

Table 3. Each turbine annual energy production

Wind Speed Bin (m/s)	**Hours per Year**	**% of hours**	**Proven WT600**	**Bergey 1kW**	**Proven WT2500**	**Skystream 2.4**	**Whisper500**
			0.6kW X 4	**1kW X 2**	**2.5 kW**	**2.4 kW**	**3 kW**
0	278	3.17%	0	0	0	0	0
1	458	5.23%	0	0	0	0	0
2	685	7.82%	0	0	0	0	0
3	925	10.56%	2775	2775	2775	2775	0
4	968	11.05%	38720	58080	72600	81312	290400
5	1216	13.88%	94848	145920	214016	246848	608000
6	1412	16.12%	190620	289460	484316	552092	1270800
7	1078	12.31%	230692	336336	609070	692076	1293600
8	677	7.73%	216640	297880	571388	656013	1117050
9	429	4.90%	175890	248820	497211	572715	900900
10	248	2.83%	139376	179800	379688	432760	644800
11	142	1.62%	88608	122830	267102	298200	426000
12	92	1.05%	57132	90620	234048	211508	294400
13	55	0.63%	33990	58850	142340	132495	181500
14	40	0.46%	24000	40000	100000	96840	128000
15	21	0.24%	12600	21000	52500	50694	65100
16	23	0.26%	13800	23000	57500	54786	69000
17	6	0.07%	3600	6000	15000	13794	16800
18	4	0.05%	2400	4000	10000	9044	10000
19	3	0.03%	1800	3000	7500	6603	6900
20	0	0.00%	0	0	0	0	0
	8760 hours						
	AEP (Wh)		1327491	1928371	3717054	4110555	7323250
	AEP (kWh)		1327.49	1928.37	3717.05	4110.56	7323.25
	Total AEP (kWh)		5309.96	3856.74	3717.05	4110.56	7323.25

$$PP = \frac{Capital\ Investment}{Annual\ Revenue - Annual\ Costs} \quad (4)$$

Here, annual revenue indicates the annual energy production, and the annual costs are consisting of operating and maintenance costs.

Net Present Value (NPV) is a measure of the attractiveness of the investment. The aim of NPV is to help to decide if the proposed small-scale wind project is an attractive investment. Equation 5 [16] is the formula used for NPV.

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$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \quad (5)$$

Here, C_0 is the initial investment shown as a negative cash flow which is subtracted from the discounted sum of cash flows. If NPV>0 then the project is profitable; otherwise it is not profitable. C_i is the cash flow at *ith* period, *T* is the period of time for analysis, *r* is the discount rate with an assumption of 0.50% annually in this case.

The cash flow (C_i) for cost and benefit analysis is calculated for a small-scale wind project is shown in Equation 6 [15],

$$C_i = Cash_{in} - Cash_{out} \quad (6)$$

Here, $Cash_{in}$ represents the net energy which means the direct benefit coming from the electricity generated by wind turbine, calculated as in Equations 7 and 8. For the first year,

$$Cash_{in} = AEP \times [Electricity\ Cost \times (1 + Electricity\ Inflation\ Rate)^{(Year-1)}] \times \left(1 - \frac{Month\ Installed}{12}\right) \quad (7)$$

Here, electricity cost represents the retail price per kWh. In Turkey, retail price is determined by EPDK, and it is \$ 0.07 per kWh (0.4612 Turkish Lira) by 2018, September [17]. Based on the manufacturer's data small-scale wind turbines typically lasts around 20 years. So, $Cash_{in}$ calculation for the next 19 years as in Equation 8,

$$Cash_{in} = AEP \times \begin{bmatrix} Electricity\ Cost \\ \times (1 + Electricity\ Inflation\ Rate)^{(Year-1)} \end{bmatrix} \quad (8)$$

Also, $Cash_{out}$ in Equation 6 is the total of initial investment (C_0), and the operating and maintenance costs (O&M costs), calculated as in Equation 9

$$Cash_{out} = C_0 + O\&M\ Cost \quad (9)$$

and the operating and maintenance (O&M) costs are negligibly small at the beginning of the installation. Equation 10 represents how the O&M Costs are calculated.

$$\sum \text{O\&M Costs} = (\text{AEP} \times \text{O\&M Cost}) \times (1 + \text{O\&M Inflation Rate})^{(Year-1)} \quad (10)$$

For a new turbine, O&M costs increase with the operating year, and are negligibly small at the beginning. This project assumes that O&M costs start from year 6, as discussed in [15]. Here, O&M cost is estimated 0.005\$/kWh based on service provider guess, and O&M inflation rate is set 3%.

Levelised Cost of Energy (LCOE) is the net present value of kWh of electricity over the lifetime of the wind energy generation system [6]. In this paper, it will be used to make comparisons with the cost of the electricity generated by small-scale wind turbine and the retail electricity price, Equation 11 is utilized for the LCOE calculations.

$$LCOE = \frac{Sums\ of\ costs\ over\ lifetime}{Sum\ of\ electricity\ produced\ over\ lifetime} \quad (11)$$

$$COE = \frac{\sum_{t=1}^{n} \frac{C_0 + \text{O\&M Cost}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP}{(1+r)^t}} \quad (12)$$

C_0 is the initial investment, O&M costs is the operating and maintenance costs, *AEP* is the annual energy production in year t, n is the lifetime of the project in years and *r* is the discount rate.

For residential small-scale wind energy production there is no grants, tax reduction, subsidies or any kind of incentives in Turkey; so installation costs cannot be reduced. Also, cash purchase is considered since the interest rates on bank loans are relatively high. And the insurance choice is not on the table in this case.

3. Results and Discussion

A cash flow analysis is done for each turbine since they all have has specific requirements. The findings of the cost and benefit analysis are summarized in Table 4.

According to the findings, it is seen that installing any five of the small-scale wind turbine system is economically viable at given costs and electricity prices. The investor's average electricity consumption per year is somewhere between 4000 kWh and 4200 kWh, so Bergey and WT2500 turbine systems cannot reach the demand.

All turbines have negative NPV over an investment period of 10 years, but reach positive NPV within their lifetime and system owners recoup costs under than 20 years. However, apart from the WT600 with a breakeven after 13 years, none of the designed systems perform well enough.

As for AEP, the four WT600 generate more energy per year than other turbines *(Bergey, WT2500 and Skystream)* and return more profit comparing to larger turbines. However, its investment cost is the most second high after Whisper500.

With Whisper500 turbine, almost no economic benefit is achievable. NPV reaches a positive value at the last year of its lifetime. As for LCOE values, this turbine performs the best among the other turbine systems, but still higher than electricity retail price at the end of 10th year. Except WT2500, all LCOEs will be lower than the electricity retail price at the end of 20th year. It means, in all four cases the investor can obtain the cost of electricity lower than the local grid's electricity retail price; WT600 reaches this point at 18th year, both Bergey and Skystream reach at 20th year, and Whisper500 reaches at 14th year.

It can be concluded that installing four of the WT600 turbine will be the most profitable investment among all these five alternatives in terms of NPV, LCOE and PP calculations.

To improve the results some recommendations may be given to the investor. Wind quality and quantity can change these results dramatically. The chosen rural case study site has a good wind resource for setting up a small-scale wind turbine system. Since the higher elevation captures stronger winds, placing the hub on a higher mast like 15m will result in better annual energy production. At this point, investor may consider increasing the tower height, by this way approximately 7-8% increase in energy output can be expected [9] which leads a feasible way to become energy independent for this site.

4. Conclusion

This paper focuses on to find the most cost-effective small-scale wind turbine system for residential use in a rural area in Turkey. First, wind resource of the site is evaluated by the actual wind data of the site that are collected from a 10m meteorological mast over one year. Annual energy demand of the investor is calculated. Then, based on average electricity consumption five different small-scale wind turbines on the market which are rated between 600W to 3kW are considered for the given site, and different system alternatives are evaluated. Annual energy production and economic aspects of each system are examined. A cost and benefit model is established, and the results for each system alternative are presented based on the Net Present Value (NPV), Levelised Cost of Energy (LCOE), and Payback Period (PP). It is found that two out of five alternatives cannot reach the investor's annual energy demand. Installing four of the smallest capacity of the wind turbine is turned out to be the most economical and beneficial investment in terms of both NPV, LCOE and PP calculations.

It can be concluded that, to arrive at the most optimal solution there is no standard case that applies for all projects. The investor has to evaluate the performance of wind turbine systems under differing site conditions and different circumstances given available wind turbines in the market.

Table 4. Summary of economic indicators

	Proven WT600	**Bergey 1kW**	**Proven WT2500**	**Skystream 2.4kW**	**Whisper500 3kW**
AEP(kWh)	5309.96	3856.74	3717.05	4110.56	7323.25
Retail Electricity Price ($/kWh)	0.07	0.07	0.07	0.07	0.07
Electricity Inflation Rate (%)	3%	3%	3%	3%	3%
Expected Lifetime (years)	20	20	20	20	20
One Turbine Cost ($)	$1,000	$1,600	$3,500	$3,300	$4,100
Total Turbine Cost ($)	$4,000	$3,200	$3,500	$3,300	$4,100
Installation Cost ($)	$2,800	$2,240	$2,450	$2,310	$2,870
Total Installation Cost ($)	$6,800	$5,440	$5,950	$5,610	$6,970
NPV -Year 5 ($)	($3,342)	($4,011)	($4,573)	($4,087)	($5,447)
NPV -Year 10 ($)	($1,225)	($2,517)	($3,139)	($2,484)	($3,844)
NPV -Year 20 ($)	$4,077	$1,222	$450	$1,528	$168
LCOE - Year 5	0.26	0.29	0.28	0.28	0.19
LCOE - Year 10	0.13	0.15	0.14	0.14	0.10
LCOE - Year 20	0.06	0.07	0.08	0.07	0.05
Payback Period (year)	13	18	19	17	20

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