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INVESTIGATION OF THE SUSTAINABILITY AND PROFITABILITY OF SMALL WIND TURBINES

ABSTRACT

In the past decades, extensive and exhaustive research has been done on the analysis of the operation of large wind turbines, but detailed analyses on small wind turbines are still rare. In addition, two current situations are considered: i) the exhaustion of the possibilities for designing new large wind fields, and ii) the energy crisis, which is particularly current in Europe, so it comes naturally to analyse the possibilities for exploitation of small wind turbines.

The paper analyses five potential locations in North Macedonia. Based on three-year measurement period at those locations, the probability distribution of wind speeds was obtained and integrated with the power curve for a specific turbine, the electricity production of four different, commercially available, small wind turbines was investigated. Three wind turbines are horizontal axes wind turbines, with installed power in the range 3-50 kWp and one is vertical axis wind turbine with installed power of 4 kWp. In accordance with the Rulebook for amending and supplementing the rulebook for renewable energy sources from June 2022, calculations have been made for the profitability of energy production from grid-connected small wind turbines.

Finally, a graphical comparative analysis of different models of small wind turbines for all locations is presented, and conclusions and further directions and recommendations for optimal utilization of wind energy are given.

Keywords: small wind turbine, wind energy, profitability

1 INTRODUCTION

Tremendous advances have occurred in the renewable energy sector in recent decades, among which one of the most important is wind energy. As shown in Figure 1, the rate of growth of global total installed wind power capacity increased annually from 2001 to 2022, [1]. The amount of electricity generated by wind increased by almost 273 TWh in 2021 (17%), 55% higher growth than that achieved in 2020 and the largest of all power generation technologies. Wind remains the leading non-hydro renewable technology, generating 1.870 TWh in 2021, almost as much as all the others combined, [2].

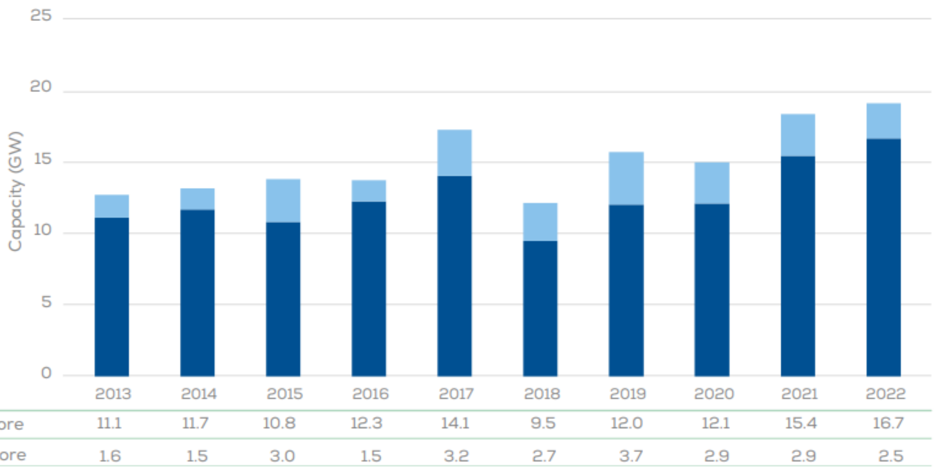


Figure 1 New onshore and offshore wind installations in Europe from 2013 to 2022, [3]

In our country, we cannot boast of following the trend of installing new wind energy capacities, as we've expected when this technology was new and promising. In 2010, the Macedonian Academy of Sciences and Arts published a strategy for the use of renewable energy sources, [4]. The study predicts that the total installed capacity by 2030 will be around 360 MW, with an expected annual production of around 720 GWh, [5]. Until the moment of writing this dissertation, only the first wind farm - Bogdanci, with an installed capacity of 36,8 MW, is operating in the country, which represents only the first phase of a projected wind farm, [6]. By the end of 2023 it is expected the second wind plant to be finished. Furthermore, this is the first private wind energy project in the country, named „Bogoslovec". "Bogoslovec" will have total capacity of 36 MW and hopefully is a step forward in order to divert country's national electricity production, which is still dominated by coal (lignite), to renewable energy sources. So it is clear that intensification of the process is needed.

1.1 The role of small wind turbines

Within the wind energy sector, small wind turbines (SWTs) are a separate group of wind turbines that cater to localized or decentralized power generation. Unlike large-scale wind turbines commonly seen in wind farms, SWTs are designed for residential, commercial, or community-scale applications. In recent years, technological advancements and increased interest in renewable energy have led to the growth of the SWTs market. As technology continues to evolve, SWTs are becoming more efficient, quieter, and aesthetically acceptable, further expanding their potential application in the renewable energy landscape.

According to the IEC 61400-2 standard, SWTs are characterized by a rotor swept area of less than 200 m^2 and rated power below 50 kW, generating electricity at a voltage below 1.000 V (AC) or 1.500 V (DC) for both on-grid and off-grid applications, [4]. Their compact size makes them suitable for installation on rooftops, towers, or other structures, and they are often used in rural or remote areas where grid connection may be challenging. They can provide power for individual homes, farms, small businesses, telecommunication units, isolated mountain objects, or even communities, reducing reliance on traditional energy sources and lowering carbon emissions. One of the primary advantages of SWTs is their ability to generate electricity in areas with lower wind speeds, as well as possibility of 24/7 electricity production. This is confirmed by data from a report from the Statista portal [5] showing the capacity of small wind turbines in the world from 2010 to 2018.

SWTs come in various designs, including horizontal-axis and vertical-axis configurations. Horizontal-axis wind turbines (HAWTs) are similar in design to larger wind turbines and consist of a rotor with two, three or more blades that rotate around a horizontal axis. Vertical-axis wind turbines (VAWTs), on the other hand, have blades that rotate around a vertical axis, allowing them to capture wind from any direction without the need for wind direction alignment.

The installation and maintenance of SWTs are generally more straightforward compared to large-scale turbines. However, it's essential to consider factors such as local regulations, zoning restrictions, and proper site assessment before installing an SWT.

While SWTs offer numerous benefits, they also have limitations. The disadvantages of SWTs are high initial cost, effective placement, wind fluctuation, lower electricity production due to wind share, change in wind direction and also aero-acoustic noise, [6]. SWT profitability is determined by the combination of wind turbine efficiency, cost and reliability. At the preliminary stage of the SWT design process, there is a need for an inexpensive, effective and reliable methodology for estimating these factors when considering design solutions and variants, [7].

The paper attempts to address this gap by examining the real parameters of SWTs, especially data on actual electricity generation and the profitability of power plant installations. The results will be valuable for economic assessments of wind turbine investments and for determining the real energy potential of SWTs in the country.

2 MATERIALS AND METHODS

2.1 Measurement data

The wind data used in the study covers a period of 3 years (2012-2015). The input data are gained form three wind measurement masts, at five different locations (Berovo, Mogila, Sopishte, St. Nagorichane and Sv. Nikole). The main parameters that are used in the analysis, wind speed and direction, are recorded at 10-minute intervals, expressed in meters per second (m/s) and degrees (º) toward north. The data used in this research are measured with anemometers and wind vanes positioned at heights of 40 m and 38 m, respectively.

In the first stage of the research, wind speeds recorded during the three year 2012–2015 period were analyzed for the five locations. Average wind speeds for each month across all years studied were calculated separately for each location. Figure 2 presents the results to facilitate the analysis of trends, differences and relationships. A constant trend of windiness between 3 and 4 m/s, can be observed across 3 locations-Berovo, Mogila and Sopishte. For Mogila it can be concluded that windiness is usually higher in the autumn-winter period than in the spring-summer period. Opposite of this, the graphs show that for Sopishte location, the windiness trend is higher in the summer months, with an exception for January. Data from measuring mast located in Berovo, also shows higher windiness trend during spring and summer months. At Sv. Nikole the windiness is between 3,7-5 m/s and higher winds are measured during warm months. Completely different windiness conditions are observed at St. Nagorichane, with wind speeds among 5,5-8,5 m/s, which qualifies this location as most suitable for exploitation of wind energy, even for commercial big wind turbines.

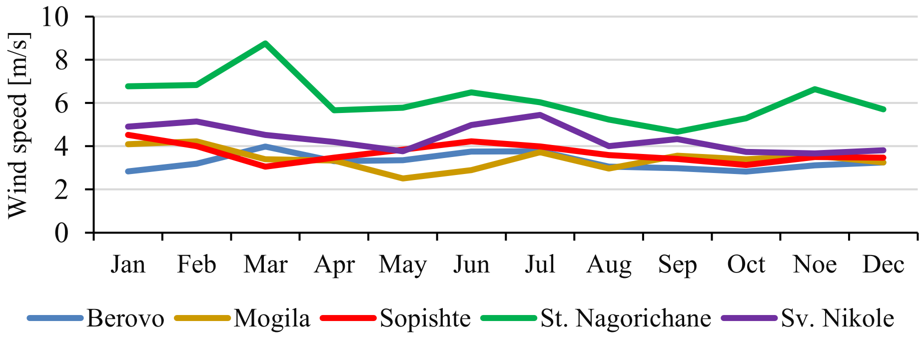


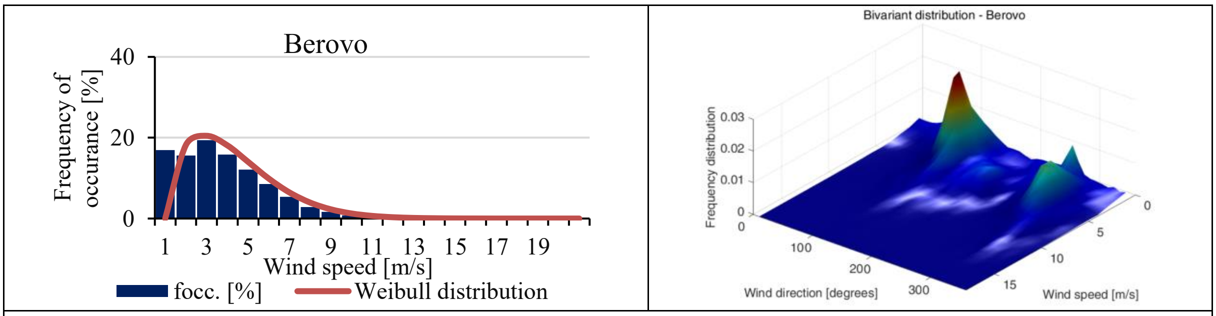
Figure 2 Distribution of mean monthly wind speeds across the three year period 2012-2015 for five locations

When analyzing data for estimation of electricity production form SWT, the absence of big variations in wind speed is a positive side. In that case, electricity generation will be quite constant and all necessary maintenance operations as well as routine checks can be carried out anytime, even it is certainly recommended to be done during the calm (least windy) periods.

Table 1 Weibull parameters for the three measuring locations

Parameter	Berovo	Mogila	Sopishte	St. Nagorichane	Sv. Nikole
v_{mean} [m/s]	3,29	3,41	3,69	6,16	4,38
Std	2,21	2,57	2,72	3,84	3,29
k	1,54	1,36	1,45	1,78	1,36
***c* [m/s]**	3,66	3,72	4,34	7,34	4,75

To more accurately depict real achievable wind speeds at these five loactions, histograms were prepared to illustrate how frequently specific wind speeds occur at each location. Also, two-parameter Weibull function is applied at the same graphs, plotted with the values for shape and scaling parameters given in Table 1. The histograms were created with instantaneous speeds from raw data recorded at a 10-minute interval. Namely, in the bivariate distribution, all wind parameters (k,c,f_{occ}) are treated as continuous variables, as a function of the angle - i.e. the direction of the wind. With this presentation in a simplified way, the convenience of applying the characteristic values of the wind as continuous variables are further emphasized. From the calculated data in Table 1 it is expected that there won't be any significant differences among wind regimes at the first three locations - Berovo, Mogila and Sopishte. All three locations are characterized with low value of mean wind speed - slightly above 3 m/s. At Berovo lowest wind speed is measured- 3,29 m/s, slightly higher at Mogila- 3,41 m/s and 3,69 m/s at Sopishte. Minor differences are calculated among shape parameters (k). Scale parameters (c) differ for Sopishte - 4,34 m/s, compared to those of Berovo, 3,66 m/s and Mogila, 3,72 m/s. This is consistent with the 3D graphs of bivariant distribution (figure 3), where it can be observed that wind has three distinguished directions at Sopishte, which can further result in dynamic changes in the directionality of wind turbine in order to face the upcoming wind. From the same graphs it is notable that at Berovo best wind regimes are in the direction among the interval [130-150]° and for Mogila this interval is [280-300]°, as judged by the peak on the surface. The dominance of all parameters values at Staro Nagorichane are evident, with the maximum measured average wind speed of 6,16 m/s, except for the k parameter-1,78 and it should be notified that a higher value was expected. The direction of the wind is most prominent in two directions, around 100 ° and 300°. At last, Sv. Nikole location is characterized with values in the middle among the above mentioned, with average wind speed of 4,38 m/s and a more wide standard deviation, compared to the first three locations. Opposite to this, the direction of the wind convincingly is in the interval [250-290]°. Wind speed analysis is the basis for calculating the annual electricity production in each location by a specific wind turbine in this study.



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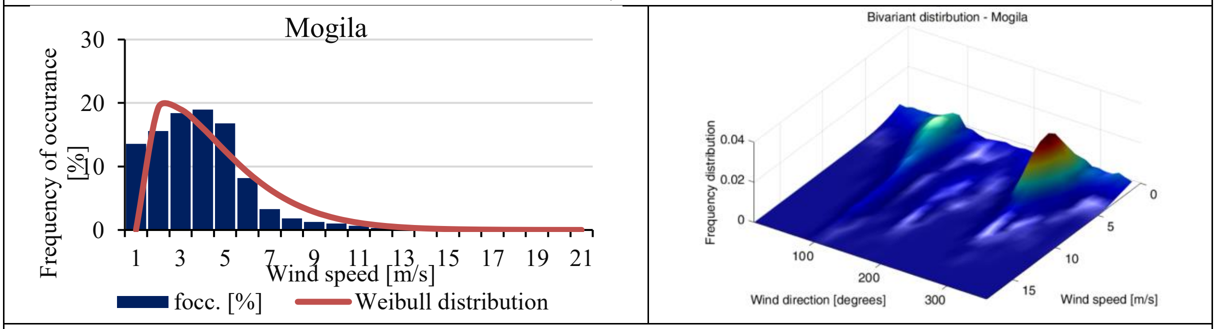

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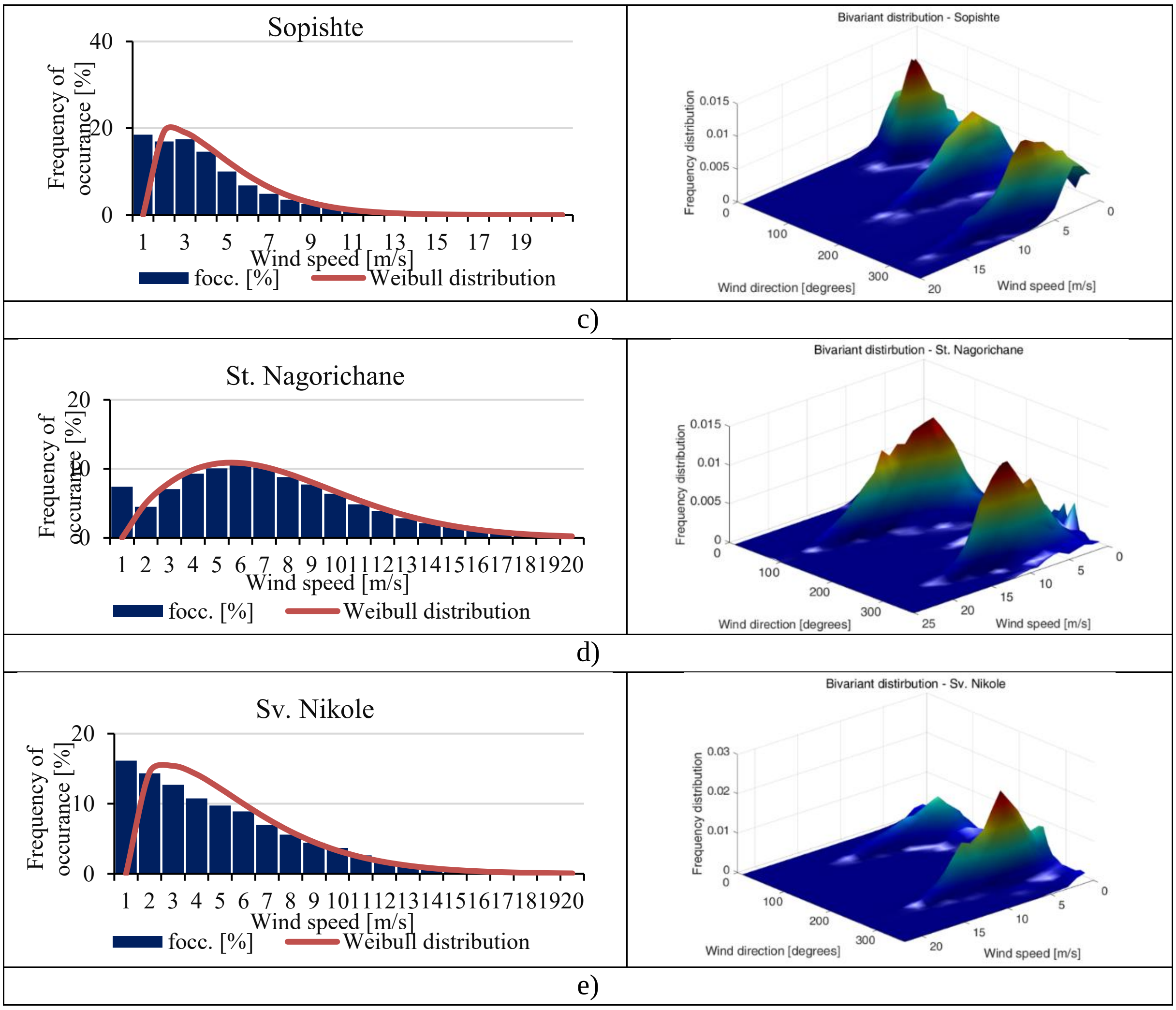

Figure 3 Wind speed distribution and bivariant distribution for a) Berovo, b) Mogila, c) Sopishte, d) St. Nagorichane and e) Sv. Nikole

2.2 Analyzed small wind turbines

The paper investigates the technical and economic feasibility of four small wind turbines at five measuring locations. The small wind turbines are with rated power of 3, 4, 30 and 50 kW. Technical data and power curve data for each wind turbine are given in Table 2. The selection of these SWT is based in the following factors: i) commercial availability, ii) online available information for installation and operating costs, iii) examining different types of turbines (VAWT and HAWT) and iv) covering widest possible range of installed power per SWT.

Table 2 SWT technical data and power curve, [8]

SWT Type/ Technical data	*Type 1:Uge-4k (Urban Green Energy - UK) VAWT*	*Type 2:Skyline sl-30 (En-Eco Italy) HAWT*	*Type 3:Hz 30 k (Ge shandong - China) HAWT*	*Type 4:Redriven 50 kW (Redriven - Canada) HAWT*
Nominal power [kW]	4	3	30	50
Rotor diameter [m]	2.75	3	12	14.3
Heght [m]	7,5	8	18	36
Investment cost [EUR/kW]	3.561,00	3.218,00	2.764,00	3.259,00
Investment cost [EUR]	14.244,00	9.654,00	82.920,00	162.950,00
Wind speed [m/s] vs. Power output [kW]				
3	-	-	-	1,5
4	0,15	0,1	1	3
5	0,3	0,2	2,5	5
6	0,5	0,3	4	7,5
7	0,65	0,5	6	11
8	0,9	0,8	9	16
9	1,25	1,1	13	23
10	1,75	1,5	17,5	32
11	2,75	2	23	40
12	3,65	2,5	31	52
13	4,15	3,25	34	55
14	4,3	3,6	29	55
15	4,25	3,6	30	55
16	4,2	3,6	30	55
17	4,15	3,6	30	55
18	4,13	3,6	30	55
19	4,1	-	30	-
20	4,1	-	30	-
21	4,1	-	30	-
22	4,1	-	30	-
23	4,1	-	-	-
24	4,1	-	-	-
25	4,1	-	-	-

The prices of the turbines are given in the same table, expressed in euros per kW [*EUR/kW*] and in euros. The net price of the turbines includes purchase cost and installation cost. Under installation cost the following cost are considered: building/foundation material cost; installation cost-crane rental, purchase of the equipment's used by the installation team; engineering cost-feasibility study; land purchase cost-circular area of the same radius is assumed necessary; grid connection cost, i.e. cables, power unit and control system and license fees, [8].The net price does not include transport and external installations including the inverter, foundation, cable connection from the power plant to the network, transformer station, etc. For easier comparison, installation cost per kW for each SWT model are given in Figure 4. From this data, the third type of SWT model is cheapest (2.764 [*EUR/kW*]) and the first type which is VAWT is the most expensive, with 3.561 [*EUR/kW*].

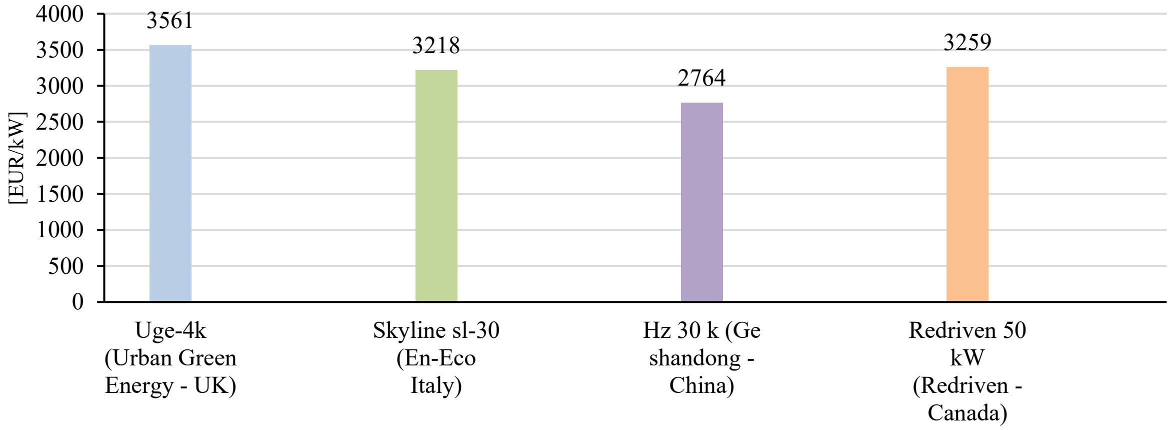

Figure 4 Investment costs referred to each turbine model

Figure 5 presents the energy characteristics of the analyzed SWTs as a power output curve, which shows the relationship between the wind speed captured by the rotor and its electrical output. The power curve allows the amount of electricity generated by the turbine to be estimated and is an essential component of wind turbine performance assessment. When the detailed characteristics of wind conditions in a given location are known, the annual electricity production of a turbine can be forecast very accurately on the basis of the power curve, and the economic viability of the investment can be assessed, [9].

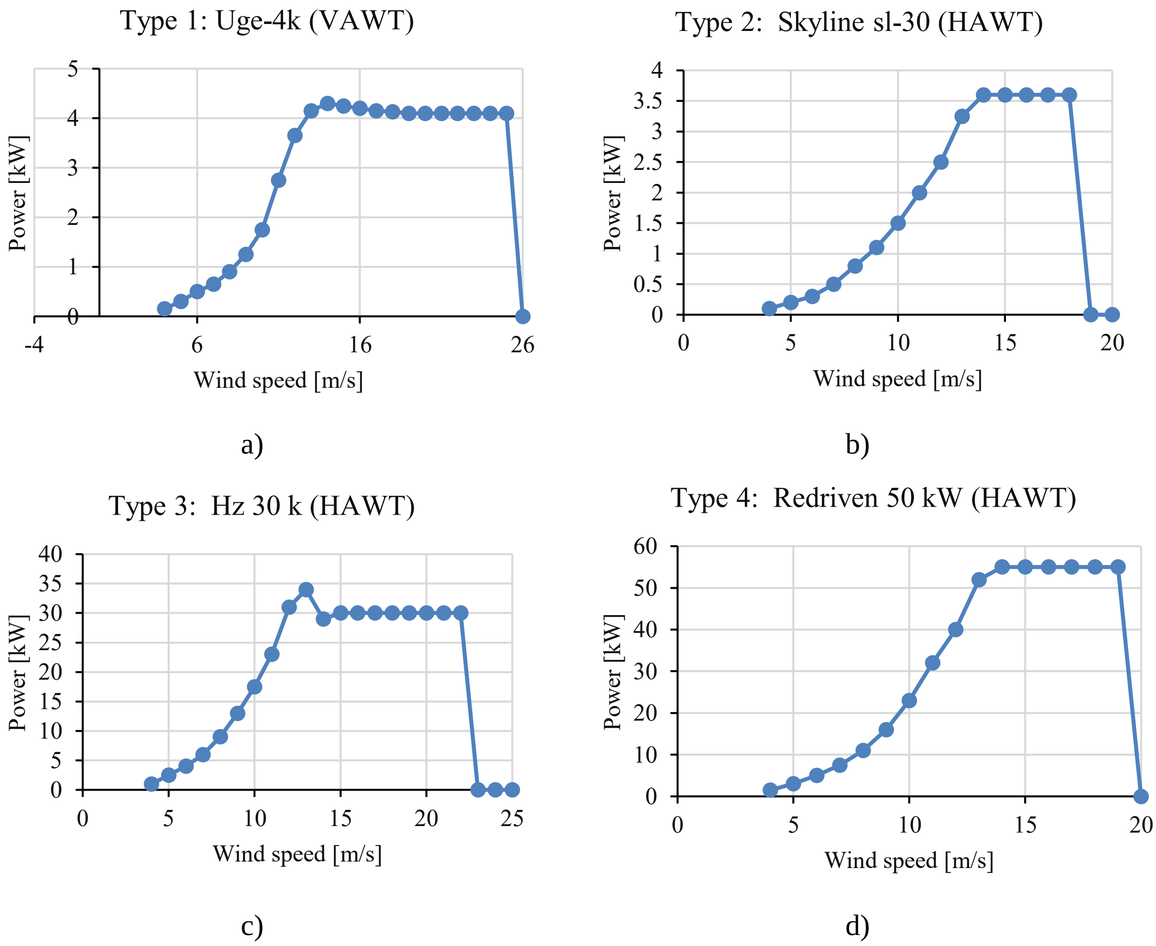

Figure 5 Power curves for four examined SWT according to data in Table 2

2.3 Economic analysis

The annual energy production (AEP) was calculated for each surveyed year for each location based on the wind characteristics, namely individual wind speeds and their frequency in a given period, and parameters from the turbine power curves for specific wind speeds. The AEP is calculated by successively multiplying the power for each wind speed from the turbine power curve by the measured wind frequency distribution and the number of hours per year. For calculating the AEP, a fixed operating period was assumed, i.e., periods out of operation (e.g., due to repair and maintenance of equipment) were not taken into account. The results are summarized in Table 3 and in Figure 6 Capacity Factors (CFs) for each SWT is illustrated for easier comparison.

The main object of the analysis is the distribution of wind speeds over the year. On its basis, the time of occurrence of winds with specific speeds during the year and, consequently, the energy production of a wind power plant is estimated. It is clear, that at St. Nagorichane highest CF values were calculated for all four types of STWs, above 27%. Data calculated for this location was not intended to be compared to other, less windy locations. Next is Sv. Nikole with calculated CFs above 13,5%. At Sopishte location generally the CF is 2% higher, compared to Berovo and Mogila.

If we analyze the SWT models, it is clear that the first type which is VAWT has lowest CFs, and the fourth type of SWT- Redriven 50 kW has a highest CFs at each location. This can be result of the lowest cut in speed, since this SWT starts producing electricity at 3 m/s, compared to the other three SWTs that start producing electricity above 4 m/s, as is shown in Table 2.

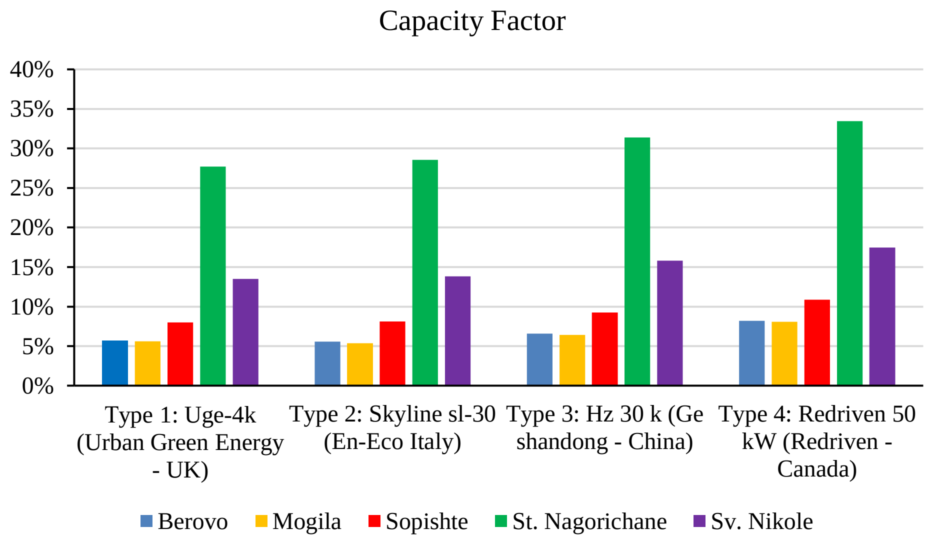

Figure 6 Calculated CF [%] for each SWT at the tested locations

In the next step, a number of calculations were performed for which the cost of electricity in Macedonia was required. The data were taken from the State Statistical Office: the average retail electricity price in 2022 for households was 6,486 MKD/kWh, which is 0,105 EUR/kWh, [10], price quoted includes all taxes and fees. In Macedonia, prosumers generating electricity for their own use sell excess produced energy to the grid, necessitating the use of two different electricity prices in the calculations. The price of the produced electricity that the supplier takes from the prosumer is determined in a manner that is established according to the Rulebook for renewable energy sources in the country:

$$c = PCE \cdot 0{,}9 \cdot E_i / E_p \tag{1}$$

if quantity of produced electricity E_p is higher of the consumed electricity E_i.

In case when consumed electricity E_i is equal to or greater than the electricity produced E_p, then:

$$c = PCE \cdot 0{,}9 \tag{2}$$

PCE is the average price of electricity that the prosumer pays to the supplier for the purchased electricity, without compensation for using the network, other fees and taxes within a calculation period, [11].

According to the State Statistical Office, the average monthly household electricity consumption was 410 kWh in Macedonia in 2022. This value was used with the average retail electricity price to calculate the price of 1,0 kWh for households.

The investment costs for each SWT type are shown in Table 2. The cost of energy (COE) was also calculated for each considered case. COE is a metric used to assess the costs of electricity generation, [12]. For one year of turbine operation, the formula for COE is as follows:

$$COE = \frac{CRF \cdot I}{AEP} + \frac{TO\&M}{AEP} \; [EUR/kWh] \qquad (3)$$

where:

- I is investment wind turbine costs [EUR],

- AEP is annual energy production [kWh],

- TO&M is total yearly operation and maintenance costs [EUR] (estimated 0,015 EUR/kWh iver the entire lifetime of the SWT, [13]), and

- CRF is the capital recovery factor. CRF is the yearly interest [%/year], which depends on interest rate i=6% and economic lifetime n=15 years.

The results of the calculations are shown in Table 3.

Table 3 Calculated Annual Energy Production and Cost of energy from each SWT

Type 1: Uge-4k (Urban Green Energy - UK)	***AEP [kWh]***	***CF[%]***	***COE [EUR/kWh]***
Berovo	1.989,67	5,68	0,74
Mogila	1.965,61	5,61	0,75
Sopishte	2.797,07	7,98	0,52
St. Nagorichane	9.703,87	27,69	0,15
Sv. Nikole	4.731,50	13,50	0,29
Type 2: Skyline sl-30 (En-Eco Italy)	***AEP [kWh]***	***CF[%]***	***COE [EUR/kWh]***
Berovo	1.460,59	5,56	0,68
Mogila	1.412,45	5,37	0,70
Sopishte	2.128,34	8,10	0,47
St. Nagorichane	7.507,10	28,57	0,13
Sv. Nikole	3.631,12	13,82	0,25
Type 3: Hz 30 k (Ge shandong - China)	***AEP [kWh]***	***CF[%]***	***COE [EUR/kWh]***
Berovo	17.296,00	6,58	0,49
Mogila	16.817,86	6,40	0,51
Sopishte	24.305,30	9,25	0,35
St. Nagorichane	82.452,12	31,37	0,10
Sv. Nikole	41.499,90	15,79	0,21
Type 4: Redriven 50 kW (Redriven - Canada)	***AEP [kWh]***	***CF[%]***	***COE [EUR/kWh]***
Berovo	35.928,32	8,20	0,47
Mogila	35.431,93	8,09	0,47
Sopishte	47.639,93	10,88	0,35
St. Nagorichane	146.578,77	33,47	0,11
Sv. Nikole	76.504,66	17,47	0,20

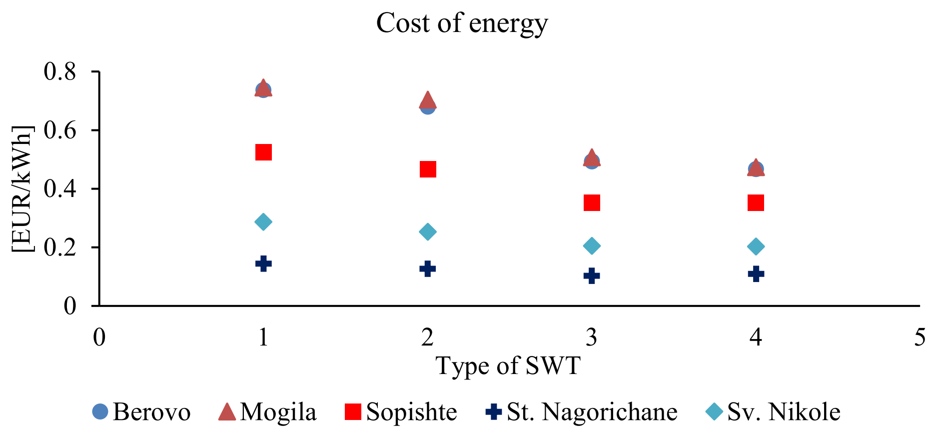

Figure 7 Unit Cost of energy production for each SWT at the tested locations

Furthermore, the return of investment in the form of payback time (SPBT) was calculated for each scenario, as follows:

$$Payback\ Time = \frac{Investment\ Cost}{Average\ Annual\ Cash\ Flow} [years] \quad (4)$$

The result is the time (in years) after which the amount of money saved from the use of a small wind turbine will exceed the amount of funds invested in the project. To assess economic efficiency, appropriate calculations were used to determine whether the investment is profitable and after what period of use the wind power plant will start to generate profit.

If the COE values form Figure 7 are analyzed it can be concluded that payback time for Berovo, Mogila and Sopishte location are very pessimistic, which will be discussed more thoroughly in the next section.

3 RESULTS AND DISCUSSION

When choosing to invest in an alternative source of energy for a household, the most important consideration is the economic aspect. The most desirable outcome is return of investment followed by the time after which the investment will start to yield a profit. By one Amendment in the Rulebook of RES, by the Macedonian Ministry of Economy, it is assumed an average rate of return on prosumer PV installations of 5-6 years. The initial idea for writing this paper was not to compare the profitability of different alternative sources, but to examine the sustainability and cost-effectiveness of SWTs for currently available commercial models.

Knowing the wind conditions at all sites, the motivation was to investigate the feasibility of SWTs at the first three sites (Berovo, Mogila and Sopishte). While performing the analyzes for annual energy production, then COE and at the end the payback time it was suggestively asserted that the same calculations should be performed for locations with better windiness, as Sv. Nikole and St. Nagorichane. Although it is known in advance that St. Nagorichane location is also eligible for the exploitation of wind energy from large scale wind farms.

The results of the simulations of energy production at the five selected locations for the period 2012–2014 are shown in Table 3, accompanied by CFs values. Based on the calculated total energy produced, location St. Nagorichane is definitely the most effective location, with more than three times greater energy production compared with either of the other locations. CF provides information about the performance of the turbine and the utilization of its potential under the given conditions. The value obtained for Sv. Nikole is good, but CFs for St. Nagorichane are optimal and indicate relatively good adaptation of all four types of SWTs to the wind conditions. However, for the first three locations, the indicator reached a very low level and it can be concluded that none of the selected turbines are not suitable for use under these conditions.

Figure 7 shows the trends in the costs of electricity generation at the five analyzed locations. Costs vary greatly depending on the location of the SWT, and Location 4 is clearly the most cost-effective. Comparing the four types of SWT, slightly lower cost are calculated for type 4 - Redriven 50 kW (0,11-0,47 EUR/kWh), compared to type 3 - Hz 30 k (0,1-0,51 EUR/kWh). The cost is lowest at St. Nagorichane for the analyzed period, with an average cost of 0,1225 EUR/kWh, in contrast to average costs of 0,24 EUR/kWh at Sv. Nikole. Average value of COE for Berovo, Mogila and Sopishte are 0,6; 0,607 and 0,42 EUR/kWh, respectively. The analysis shows that Mogila is the most expensive-this can already be deduced from the value of the AEP index, which is the lowest at all four types of SWT. The cost calculations show the same for all locations, so if the least amount of electricity was produced during the year, the highest cost of electricity generation per kWh is gained.

A wide range of investment payback periods is obtained, highlighting the importance of a proper, in-depth analysis of location in the preliminary design of SWT installations and before the start of the investment. In the Rulebook for renewable energy sources for North Macedonia, it is clearly noted that a facility for the production of electricity from a renewable energy source can be build, since it uses the electricity produced for its own consumption, and the surplus of the electricity produced is handed over to the electricity distribution network only if:

i) the installed power of the facility should not exceed 6 kW, for household use,

ii) the installed power of the facility should not be greater than 40 kW, for a small budget company.

Due to these limitations, for the SWT type 3 and type 4 (with installed power of 30 kW and 50 kW, respectively) in the calculations, very small, almost none money returns are obtained from the delivered electricity (Eq. 1), so the calculated payback time is over 95 years. The best result was obtained for SWT type 2 (Skyline SL-30,3 kW) which is 15,99 years for the payback period, certainly at St. Nagorichane location.

If the profit was the main objective, the installation of a SWT is not the best option for households. Maybe it is reasonably to analyze the operation of the SWT under isolated conditions from the power grid, when it is unprofitable and unreasonable to connect a particular facility to the grid.

Other option can be a turbine with a shrouded rotor (diffuser). Despite extensive study, shrouded turbines are not yet widely used due to their complexity and high design and manufacturing costs. The diffuser acts as a wind gathering and accelerating device, allowing the turbine to achieve higher aerodynamic efficiency than allowed by the Betz limit, [14] [15].

4 CONCLUSION

The basic knowledge necessary for deciding to invest in a wind turbine in a given area is local wind energy resources. The results of the present paper emphasize the potential for large differences in average annual speed among measurement points and hence the importance of measurement of wind characteristics for decision-making. Wind potential clearly differs among the selected five locations and therefore consequently the per unit cost of electricity follows these differences.

Based on the results of this analysis, the following conclusions can be withdrawn:

i) The wind characteristics in the analyzed locations Berovo, Mogila and Sopishte have a similar windiness trend, so we analyze them in one separate group. Sv. Nikole has slightly better wind regimes, but undoubtedly St. Nagorichane has the most desired wind regimes.

ii) The per unit cost of electricity generation is clearly different in each „group”. This proves the necessity of thorough verification of the surroundings before investing in a SWT.

iii) The most favorable location for SWT installation from analyzed five locations is St. Nagorichane location.

iv) The conducted analysis gives an overview of the costs of wind resources in different parts of the country, but it is not truly complete as the authors did not have all the required data for calculations, and therefore they partly used assumptions from the literature.

v) Current SWTs are promising solutions for use in sparsely populated areas where there is no access to electricity from the distribution grid.

vi) The addition to SWTs of equipment such as diffusers to tunnel the rotor could increase SWT efficiency and promote further growth of the wind energy industry. Rotor tunnelling can also ensure efficient wind turbine operation, even in areas with less than ideal wind conditions.

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