Small-scale 10 kW wind turbine on-grid connected for power supply of two different consumers

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Abstract. In this paper a power supply system based on a 10-kW wind turbine on-grid connected used for two different consumers is analysed. The proposed wind turbine site is located at coordinates 46°57'41''N 25°56'36'' E, in the Ceahlău National Park, on the plateau of Ceahlău Mountain. Nearby there are located the two consumers: the Ceahlău Monastery and the Dochia Chalet. The site wind resource is obtained mainly from NASA Surface meteorology and Solar Energy database. The load demand curves, the annual energy consumption and the peak load are obtained considering the standard load profile for these two particular types of consumers. The on-grid power supply system is analysed using HOMER Energy microgrid modelling software for different tourist's occupancy. Two different wind turbines (XZ and XL) with rated power of 10 kW are comparatively analysed. Selection of the most suitable wind turbine is realized using the Weighted Product Method (WPM), for which nine attributes are used: annual energy production, capacity factor, renewable fraction, grid purchase, grid sales, initial investment, net present cost, levelized cost of energy, and simple payback. For a given criteria weights, the XL model is found to be the most suitable wind turbine.

1. Introduction

The most important planning task required for wind turbine project development is finding a suitable site and selecting the most suitable wind turbine for that site. This is a multi-dimensional criteria decision-making problem for which different solving methods can be used.

For general projects in renewable power supply systems, the most important aspects related with the criteria selection, criteria weighting and solving methods are presented in [1]. In [2], 4 wind turbines with rated power of 1.5 MW are analyzed from the point of view of 13 technical, economic, environmental and customer attributes using the Analytical Hierarchy Process (AHP). In [3], 18 wind turbines have been analyzed in terms of 5 technical only attributes using the Weighted Sum Method (WSM). The Fuzzy Analytic Network Process (FANP) has been used in [4], for decision making in a multi-criteria problem with 4 multi-megawatt wind turbines and 14 machine characteristics, economic aspects, environmental issues and technical levels.

In this paper a wind turbine-based power supply system on-grid connected for two different consumers will be presented. The power supply system is site dependent and is modelled and simulated using HOMER Energy microgrid modelling software, [5]. For one consumer, nine different annual energy consumptions will be considered, thus defining a sensitive parameter. Two wind turbines (XZ and XL) with rated power of 10 kW will be analysed. Compared with the reference power supply system

based only on the national electric grid, both wind turbines have been found that are feasible in terms of net present cost and CO_2 emissions. The most suitable wind turbine for the proposed site will be selected using the Weighted Product Method (WPM) considering 5 technical attributes (annual energy production, capacity factor, renewable fraction, grid purchase, and grid sales), 4 financial attributes (initial investment, net present cost, levelized cost of energy, and simple payback) and a given set of criteria weights related with a certain project development strategy.

2. Site location and wind resources

The wind turbine site proposed for this analysis is located in Romania, in Neamț County, at the coordinates 46°57.7' N 25°56.6' E, in the Ceahlău National Park, on the plateau of Ceahlău Mountain. The power supply system analysed in this study is based only on a single form of renewable energy, which is the wind energy, so only the wind resource will be considered. The wind turbine power output depends also on the air density, which is highly influenced by the temperature, as consequence, for this study, the annual air temperature variation will be also considered.

The temperature data will be obtained from NASA Surface meteorology and Solar Energy database (NASA Langley Research Centre Atmospheric Science Data Centre Surface meteorological and Solar Energy (SSE) web portal supported by the NASA LaRC POWER Project), [6]. The monthly average temperature data for the selected site are presented in figure 1. The maximum temperature is 18.63 °C in July, while the minimum temperature is -6.5 °C in January, the temperature range being 25.13 °C. The annual average temperature is 6.5 °C.
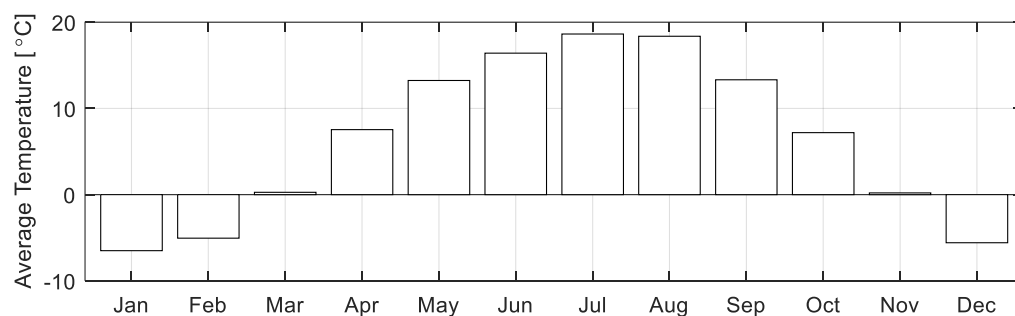

Figure 1. The monthly average temperature.

As for wind speed, let us assume that by on-site measurement at anemometer height of 50 m, the following annual wind speed distribution has been obtained, figure 2. The measurement process has been defined with 30-seconds measurement time span, and 1-hour average time span, so there are 8760 data points.
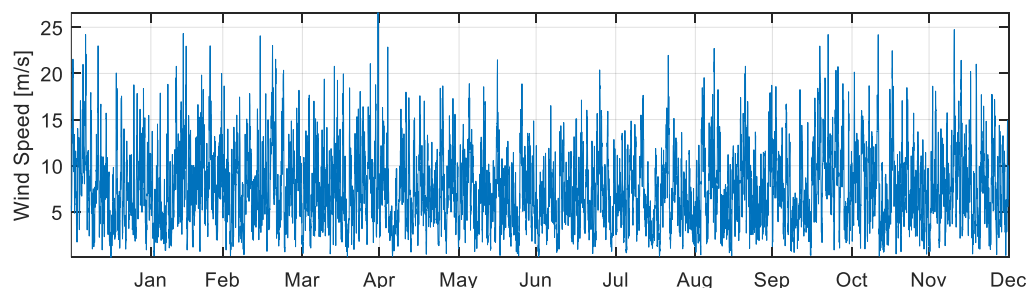

Figure 2. The annual wind speed at 50 m.

Analysing the wind speed data, the following parameters has been obtained: the annual average wind speed V_m=7.6 m/s; the standard deviation of wind speed distribution σ_V=4.0977 m/s; the wind speed turbulence intensity I_t=53.93; the Weibull shape factor k=1.95; the Weibull scale factor A=8.56 m/s. The wind speed histogram is presented in figure 3. The wind speed power density P [W/m^2], is presented in figure 4, for which the total power density is 524.88 W/m^2.
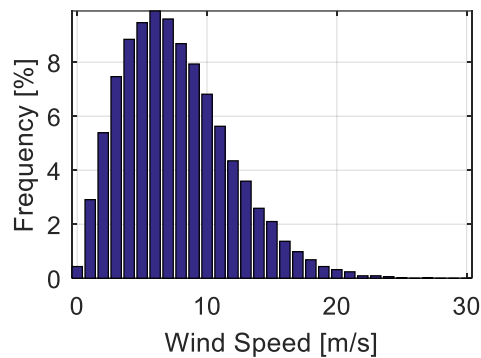
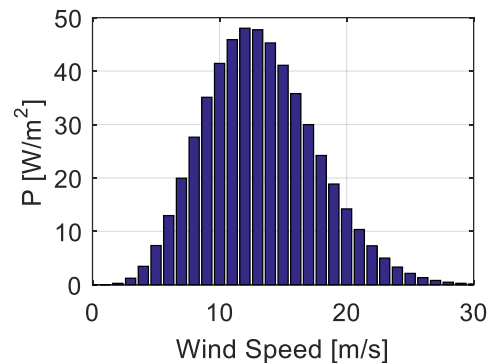**Figure 3.** The wind speed histogram.

Figure 4. The wind speed power density.

3. Electric load

The wind turbine on-grid connected power supply system is supposed to supply electricity for two consumers in the vicinity of the wind turbine site: the first consumer is the Dochia Chalet, and the second consumer is the Ceahlău Monastery.

For the Dochia Chalet, different tourist's occupancy has been considered, {20, 30, 40, 50, 60, 70, 80, 90, 100} %, for which the following load parameters have been obtained: the annual energy consumption {9360, 13140, 20700, 24480, 28260, 32040, 35820, 39600} kWh/year, and the daily average energy consumption {25.64, 36, 46.35, 56.71, 67.07, 77.42, 87.78, 98.14, 108.49} kWh/day. The daily average load profile for 50% tourist's occupancy is presented in figure 5, a).

For the Ceahlău Monastery, the residential load profile has been considered, with the following parameters: the annual energy consumption 7200 kWh/year; the daily average energy consumption 19.72 kWh/day; the daily average power 0.82 kW, and peak load 4.06 kW. The daily average load profile is presented in figure 5, b).
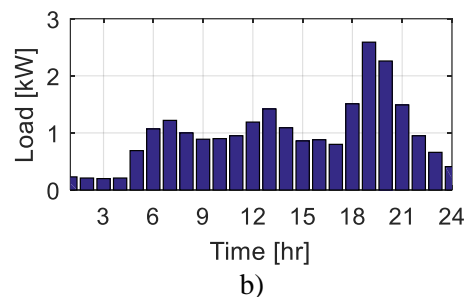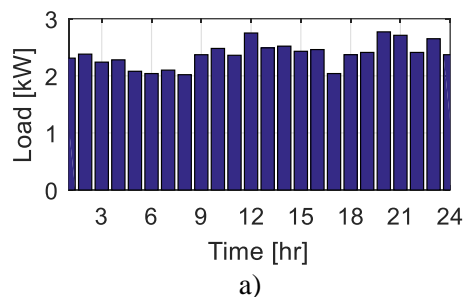

a)

b)

Figure 5. Daily average load profile.

4. On-grid power supply system

The power supply system configuration, the simulations and the optimization computation have been made using HOMER (Hybrid Optimization of Multiple Energy Resources) Energy software, [5]. The power supply system is composed by two electric loads, the grid and the wind turbine, figure 6. The principal characteristics of the power supply system are: 20 years lifetime; 0.1057 €/kWh grid power price; 0.09 €/kWh grid sellback price; 2% expected inflation rate, and 3% nominal discount rate. The electricity price, with all taxes included, has been obtained from EUROSTAT database, for non-household consumers in consumption band IB, 20 MWh÷500 MWh, for the 1st semester of 2017, [7].

For this study, two wind turbines will be comparatively analysed: XZERES 442SR 10 kW (XZ), [8] and Bergey Excel 10 kW (XL), [9]. The principal characteristics of these two wind turbines are presented in table 1. The power curves are presented, comparatively, for both wind turbines in figure 7. The standard hub height for both wind turbines is 24.4 m. The reference wind speed for the selected site is obtained at the anemometer height, which is 50 m. For extrapolating the wind speed at the hub height, the wind speed logarithmic profile is considered, with surface roughness length of 0.1 m, which correspond to few trees site type.

The existing carbon dioxide penalties vary from less than US\$1/tCO$_2$ (Poland, Ukraine, Mexico) to US\$140/tCO$_2$, (Sweden), [10]. Let us consider in this study the carbon dioxide penalties of 50 €/tCO$_2$.

Table 1. Wind turbines characteristics.

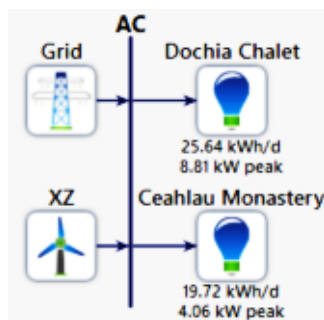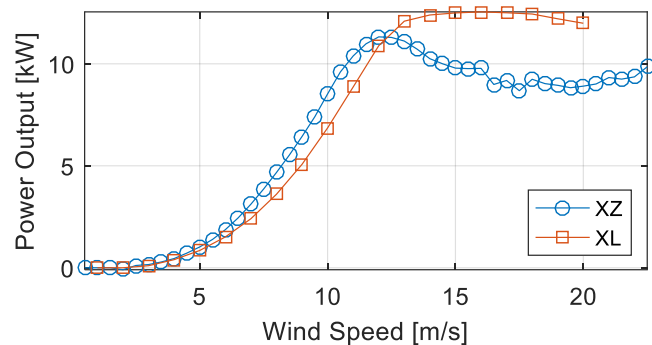|	XZ	XL
Rated power, [kW]	10.4	8.9
Rated wind speed, [m/s]	11	
Cut in wind speed, [m/s]	2.5	3.4
Rotor diameter, [m]	7.2	7
Number of blades	3	
Hub height, [m]	24.4	
Generator	Permanent Magnet Alternator	
Availability losses, [%]	0.5	
Environmental losses, [%]	1.0	
Operating life, [years]	20	
Total investment cost, [€]	55905	40000
Annual maintenance and operation cost, 1% [€]	559	400

**Figure 6.** The power supply system.

Figure 7. The wind turbines power curves.

5. Methodology

The reference case for this study is referring to the power supply system based only on the national grid. Two other power supply systems, based on the 10 kW wind turbines XZ and XL will be analysed. For comparing and ranking these two power supply systems with respect to the reference case, two parameters will be used: the net present cost, and the carbon dioxide emissions. Considering the tourist's occupancy values, the optimal curves for the net present cost and the carbon dioxide emissions will defines two areas: the red area, which corresponds to the prohibitive systems, and the white area, which correspond to the feasible systems. The wind turbine power supply systems will be compared with the reference case, and between each other, considering not only the net present cost and the carbon dioxide emissions, but also other parameters, like wind turbine energy production, energy purchased from the grid, energy sold to the grid, renewable fraction and simple payback.

6. Results and discussion

Considering the net present cost as first objective function, both wind turbine power supply systems are placed in the white area, thus are feasible systems, with XL wind turbine as the best option, figure 8. On the other hand, with respect to the second objective function, which is the carbon dioxide emissions, both wind turbine power supply systems are feasible systems as well, but with XZ wind turbine as the best option, figure 9.
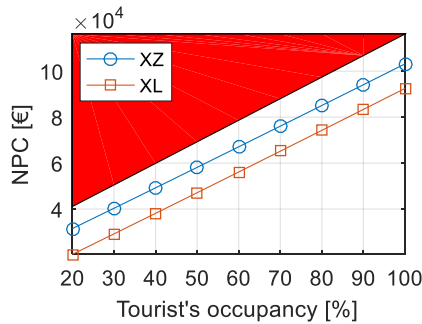
Figure 8. The net present cost.
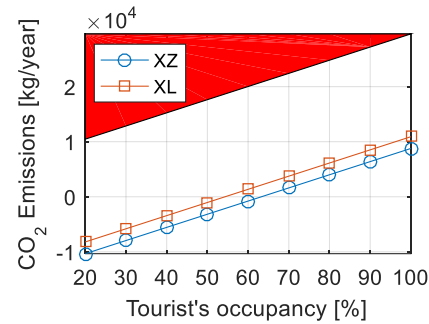
Figure 9. The carbon dioxide emissions.

Considering the amount of energy exchanged with the grid, the XZ wind turbine is also the best option, because no matter the tourist's occupancy, the energy purchased from the grid is lower (figure 10), and the energy sold to the grid is higher (figure 11) than the power supply system with the XL wind turbine. These results are a consequence of the fact that the XZ wind turbine power curve is more adapted with the site wind resource, so the energy produced will be higher than for the case of the XL wind turbine, the XZ wind turbine being the best option from the point of view of the correlation between wind turbine power curve and the site wind resource.
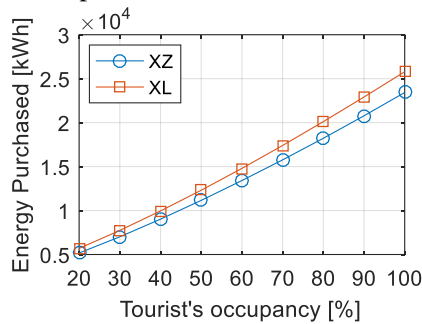
Figure 10. The energy purchased from the grid.
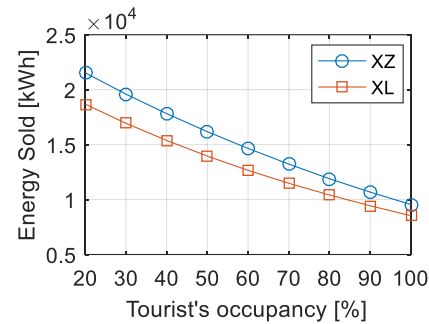
Figure 11. The energy sold to the grid.

For a certain tourist's occupancy, the consumers power demand is the same for both power supply systems. The energy production, which is depending of the wind turbine type, represents only a part of the energy demand, the rest being purchased from the grid. When the energy produced by the wind turbine is greater than the energy demand, the energy surplus will be sold to the grid. If energy demand is increasing (for example with the tourist's occupancy), for the same wind turbine, the energy purchased from the grid will increase, while the energy sold to the grid will decrease. It is interesting to note that for a certain energy demand (critical tourist's occupancy) the energy purchased from the grid will be equal with the energy sold to the grid. This critical tourist's occupancy is around 63% for the XZ wind turbine (figure 12), and around 54% for the XL wind turbine (figure 13). Only bellow this critical point, the energy sold to the grid is greater than the energy purchased from the grid. Thus, considering the critical tourist's occupancy for which the energy sold is equal to the energy purchased, the XZ wind turbine will be also the best solution.

One of the design parameters of the power supply system is the renewable fraction, i.e. the percent of energy produced by the renewable sources, in this case by the wind turbine. Considering this parameter, the XZ wind turbine is also the best option, no matter the tourists occupancy, the renewable fraction for this wind turbine being greater than for the power supply system based on the XL wind turbine, figure 14. On the other hand, considering the simple payback design parameter, the best option will be the power supply system with XL wind turbine due to lower initial investment. For example, if we consider the tourists occupancy of 50%, the simple payback of the power supply system with the XL wind turbine will be 11.64 years, while for the XZ wind turbine the simple payback will be 15.08 years, which is really a significant difference.
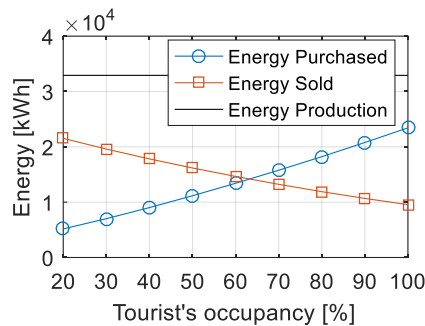
Figure 12. The energy for XZ wind turbine.
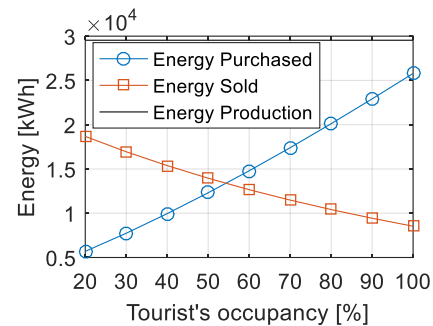
Figure 13. The energy for XL wind turbine
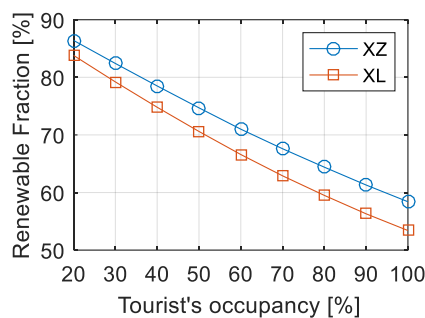
Figure 14. The renewable fraction.
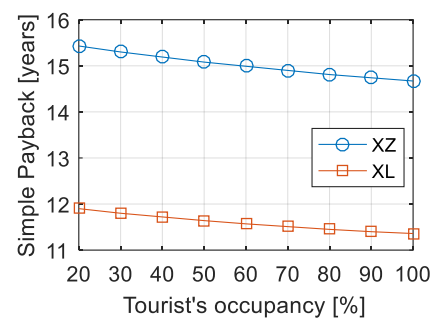
Figure 15. The simple payback.

Let us consider only the case when the tourist's occupancy is equal with 50%. In table 2 there are presented some of the technical and financial parameters for both wind turbine-based power supply systems, compared with the grid only supply power system. Both power supply systems are feasible in terms of NPC and CO_2 emissions. Moreover, because of the negative net grid purchase (grid purchase minus grid sales), the CO_2 emissions are negative too. HOMER calculates the CO_2 emissions by multiplying the net grid purchase with the emission factor (0.632 kgCO_2/kWh). The power supply system with XZ wind turbine is the better option in terms of energy production, renewable fraction and CO_2 emissions, while the power supply system with XL wind turbine is the better option in terms of NPC, COE and simple payback.

Table 2. Power supply systems parameters for 50% tourist's occupancy.

	Grid only	XZ	XL
Load, [kWh/year]	27898	27898	27898
Capacity Factor, [%]	-	36.1	33.7
Hours of Operation, [hrs/year]	-	7986	8115
AEP (Annual Energy Production), [kWh/year]	-	32917	29540
Grid Purchase, [kWh/year]	27898	11156	12312
Grid Sales, [kWh/year]	-	16175	13954
Renewable Fraction, [%]	-	74.7	70.6
Simple Payback, [years]	-	15.08	11.64
CO_2 emissions, [kg/year]	17631	-3172	-1038
NPC, [€]	69258	58145	47116
COE, [€]	0.137	0.073	0.0623

7. Selection of the most suitable wind turbine
Selection of the most suitable wind turbine, between the m=2 alternatives, XZ and XL, is a complex process based on some of the most important attributes discussed above. Let us consider n=9 attributes used for decision making process: technical criteria (AEP, [kWh/year]; capacity factor, [%]; renewable

fraction, [%]; grid purchase, [kWh/year]; grid sales, [kWh/year]), and financial criteria (initial investment, [€]; NPC, [€]; COE, [€]; simple payback, [years]). All these criteria are quantitative, but some of them are of benefit type (AEP, capacity factor, renewable fraction, grid sales), meanwhile the others are of cost type (initial investment, NPC, COE, simple payback, grid purchase). This is a multi-dimensional criteria decision-making problem, which will be solved using the Weighted Product Method (WPM). The decision matrix for 50% tourist's occupancy is presented in table 3.

Table 3. Decision matrix for 50% tourist's occupancy.

Rank	Decision criteria	Weight, W_j	Normalized Weight w_j	Raw score x_{XZ_j}	Raw score x_{XL_j}	Weighted normalized score $\left(\dfrac{x_{XZ_j}}{x_{XL_j}}\right)^{\pm w_j}$
1	AEP, [kWh/year]	9	0.200	32917	29540	1.0219
2	NPC, [€]	8	0.178	58145	47116	0.9633
3	Initial investment, [€]	7	0.156	55905	40000	0.9493
4	Simple payback, [years]	6	0.133	15.08	11.64	0.9661
5	COE, [€]	5	0.111	0.0703	0.0623	0.9825
6	Grid sales, [kWh/year]	4	0.089	16175	13954	1.0132
7	Grid purchase, [kWh/year]	3	0.067	11156	12312	1.0066
8	Renewable fraction, [%]	2	0.044	74.7	70.6	1.0025
9	Capacity factor, [%]	1	0.022	36.1	33.7	1.0015
				Weighted Product, $R(XZ/XL)$		0.9083

While the ranks represent the preference order of each criterion (the most preferred criterion has the rank 1), the weights W_j represent the importance of each criterion $j = 1 \div n$ (the most important criterion has the weight 9). The normalized weights w_j are calculated with formula:

$$w_j = \frac{W_j}{\sum_{j=1}^{n} W_j}, \qquad (1)$$

where $\sum_{j=1}^{n} w_j = 1$.

The weighted product for comparing the alternatives XZ with XL is calculated with formula:

$$R(XZ/XL) = \prod_{j=1}^{n} \left(\frac{x_{XZ_j}}{x_{XL_j}}\right)^{\pm w_j}, \qquad (2)$$

where x_{XZ_j} and x_{XL_j} are the raw scores of XZ and XL alternatives in terms of j-th criterion; $+w_j$ is taken for benefit criteria, and $-w_j$ for cost criteria.

As the weighted product is 0.9803<1, the decision is that the alternative XL is more desirable than alternative XZ.
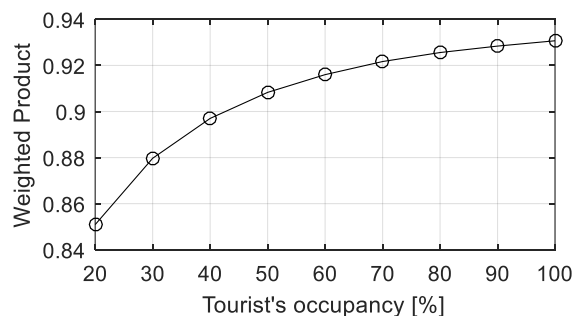

Figure 16. Weighted product for comparing the XZ and XL wind turbines.

The weighted product results obtained for all tourist's occupancy values are presented in figure 16. For all tourist's occupancy, the XL wind turbine is most desirable. However, working at low tourist's occupancy is preferred.

8. Conclusions

The most suitable wind turbine selection, for a certain location and for a certain load profile, cannot be made considering only the annual energy production, which indeed is considered to be the most important decision criterion, but that is not enough for a comprehensive decision. Moreover, the number of criteria that indicates that a certain wind turbine is the most suitable is not necessarily relevant for the final decision. For this study, all these aspects indicate that XZ wind turbine should be the best option. However, the final decision obtained by Weighted Product Method indicates, contrary to all these expectations, that the XL wind turbine is the most suitable for the power supply system analysed. What is more important for decision making process, are the relative differences between the raw scores, and most of all, the criteria weights.

The decision presented in this paper has been made for a certain set of criteria weights. Probably, for other criteria weights, the final decision could be different. Thus, it is very important the strategy used for project development. For this study, has been considered a strategy oriented primarily to prioritize the maximization of the annual energy production and the minimization of the net present cost, the initial investment, the simple payback and the levelized cost of energy, while the other attributes (grid sales/purchase, renewable fraction, and capacity factor) have less importance.

9. References

[1] Wang J J, Jing Y Y, Zhang C F and Zhao J H 2009 Review on multi-criteria decision analysis aid in sustainable energy decision-making *Renewable and Sustainable Energy Reviews* **13** pp 2263-2278

[2] Sagbansua L and Balo F 2017 Multi-criteria decision making for 1.5 MW wind turbine selection *Procedia Computer Science* **111** pp 413-419

[3] Rehman S and Khan S A 2017 Multi-Criteria Wind Turbine Selection using Weighted Sum Approach *International Journal of Advanced Computer Science and Applications* **8** pp 128-132

[4] Lee A H I, Hung M C, Kang H Y and Pearn W L 2012 A wind turbine evaluation model under a multi-criteria decision making environment *Energy Conversion and Management* **64** pp 289-300

[5] HOMER Energy The HOMER Pro microgrid software, https://www.homerenergy.com/index.html, accessed at 15.11.2017

[6] NASA Atmospheric Science Data Centre, Surface meteorology and Solar Energy Database, https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi, accessed at 26.12.2017

[7] European Commission, EUROSTAT, Electricity prices for non-household consumers, http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do, accessed at 2.01.2018

[8] XZERES 2017 XZERES 442SR Wind Turbines http://www.xzeres.com/wind-turbine-products/xzeres-442sr-small-wind-turbine/, accessed at 1.01.2018

[9] Bergey 2017 The Excel 10 kW wind turbine, http://bergey.com/products/wind-turbines/10kw-bergey-excel, accessed at 2.01.2018

[10] World Bank Group, State and Trends of Carbon Pricing, 2017, http://documents.worldbank.org/curated/en/468881509601753549/State-and-trends-of-carbon-pricing-2017, accessed at 27.12.2017