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## WIND TURBINE SELECTION METHOD BY USING ANALYTICAL NETWORK PROCESS ASSOCIATED WITH COST BENEFIT ANALYSIS

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### Abstract

Wind turbine evaluation is very crucial in the overall effectiveness of a wind project where the stakeholders are challenging for selection among very different wind turbines. Consequently, this study proposes a method which incorporates analytic network process and cost benefit analysis to choose appropriate turbines during development and investment of a wind plant. A case study is implemented for performance evaluation of various wind turbine types, determining the evaluation priority of factors for wind turbine selection and ranking the turbine performance with respect to key cost and natural parameters. Sensitivity analysis is studied to analyse the stability of method outputs to changes in parameter values. Cost benefit analysis of different turbines is carried out in terms of internal rate of return and net present value. Several scenarios of technical and economical input parameters are vital in order to examine turbine performance under different conditions since the importance of each parameter varies considerably depending on chosen turbine technology. It is aimed to highlight that even minor changes in these parameters may have a serious variation on decision making with no uniform criteria but a combination of indices is most preferable.

*Key words:* analytic network process, cost benefit analysis, multi-criteria decision-making, sensitivity analysis, wind energy economics

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### 1. Introduction

A wind project includes three major types of costs: capital costs, financing costs and running cost. Capital costs consist of all construction costs of plant and connection of it to the grid; financing cost is the cost of fund acquisition for building and running a wind plant; and the running costs involve the operational and maintenance costs of the project. The wind turbine cost has majority of total capital cost in a wind project (Renewable UK, 2011) so that the selection of suitable wind turbines is highly important. As power ratings of wind turbine technology goes up, unit selection will become more critical due to raised portion of it in overall scope. However, the use of multicriteria decision-making (MCDM) methodologies like analytical network process (ANP)

considering uncertain and stochastic information to handle the complicated problem is limited. Sedaghat et al. (2019) have introduced a strategy for selection of wind turbine using rated wind speed optimization and concluded that there are limits for the costs and optimum rated power. Rosales and Gomez (2018) have studied a method for wind turbine selection using statistical analysis for the cost of energy estimation and established models to use for the selection method proposed. Gualtieri (2019) has developed a method for detection of an optimized wind farm layout driven by the several wind turbine characteristics.

ANP is generalization of analytic hierarchy process (AHP). It is a MCDM method to separate a complicated problem into a network when relations between elements are not easily shown as lower or higher, directly or indirectly. A "supermatrix" is

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formed after analyzing the priority of elements and inter-relationship between them.

ANP was frequently implemented in diverse areas in recent years. Önit et al. (2008) have chosen the ANP to analyze most appropriate energy resources for Turkish industry. ANP has been used for the evaluations of power plant and identification of suitable energy policy in Turkey (Atmaca and Basar, 2012; Dagdeviren and Eraslan, 2008; Ulutas, 2005), for the evaluations of generating electricity from alternative technologies in India (Nixon et al., 2013). Fuzzy ANP method used to select an appropriate location for developing a wind plant (Kang et al., 2011). Several studies (Ebenhoch et al., 2015, Kim and Kim, 2016; Schroeder et al., 2013; Stehly et al., 2017) have been made in literature where technical and economical comparison of different turbine types. Maximizing annual energy production (AEP), minimizing levelized cost of energy (LCOE) and turbine configuration to AEP are examined in these studies (Barthelmie and Pryor, 2013; Herbert-Acero et al., 2014). Sensitivity analysis (SA) was also implemented in the research of parameters influencing wind energy investment. Tong et al. (2015) analyzed the sensitivity of the wind plant output to installed capacity, land configuration and wind conditions. Dykes et al. (2012) showed the sensitivity of the cost of an offshore plant to main turbine parameters. Capps et al. (2012) performed the sensitivity of energy yield of a wind plant to key design parameters. Techno-economical investigation of the effect of wind plant-scale natural and cost parameters on investment is however rare in the literature.

In first section of this study, technical evaluation of selected wind turbine generators (WTG) has been completed by means of grid connection availability and energy quality as per given grid code (TEMRA, 2017; Uzunlar et al., 2015). Only feasible product solution of different manufacturers is chosen in order to achieve better optimization in this second economical evaluation section of the study by using CBA and SA with respect to three key investment parameters decided by ANP.

The purpose of using an ANP based decision making approach in this study are: (i) they allow decision maker (DM) to evaluate complicated MCDM problems using a systematic approach that decomposes main problem into easier sub problems, (ii) ANP is used if there are interdependencies between groups of elements, (iii) detailed analysis of interdependencies and priorities between elements pushes DM to carefully reflect on the decision-making problem itself and on his project priority approach, which results in a more reliable final decision and a better understanding of the problem.

## 2. Methodologies

### 2.1. Overview of analytical network process

ANP shows a MCDM problem as a network of elements grouped into clusters. All elements in network can have interdependent relations between and within clusters. This provides a more proper modelling of complicated problems. ANP model (Eq. 1) contains steps listed below:

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & 1 \end{bmatrix} \tag{1}$$

where:  $a_{ji} = 1/a_{ij}, i, j = 1, \dots, n$

- 1) Build a model collecting the elements into  $c_1, c_2, \dots, c_G$  clusters.
- 2) Identify elements' relationships and obtain elements' relationships matrix.
- 3) Obtain clusters' relationships matrix.
- 4) Compare the influence of elements that belongs to each cluster on any element, and derive priority vector to obtain unweighted supermatrix,
- 5) Conduct pairwise comparisons on the clusters and obtain clusters weights matrix.
- 6) Calculate the  $N \times N$  weighted supermatrix, as shown in Table 1.
- 7) Calculate the  $N \times N$  normalized and weighted supermatrix.
- 8) Raise the weighted supermatrix to limiting powers until the weights remain stable and converge.

### 2.2. Overview of cost benefit analysis (CBA)

Factors influencing the wind investment may be split into two categories as cost and natural parameters. Natural parameters are the variations of wind elements like wind speed, turbulence and shear at the given plant which can't be managed through design or optimization but cost parameters are usually adjusted by design features like turbine components including hub height, rotor diameter and also economical parameters. These parameters adjusting the investment in turn affect the wind plant feasibility. So, the reliability of wind plant investment depends on the cost model accuracy and on the assumptions connected to the cost and natural parameters.

CBA consists of not one but a set of analytical instruments that used to analyze the economic and financial feasibility of an investment. Some of the analytical tools that can be used include: Net Present Value (NPV); Internal Rate of Return (IRR); Sensitivity Analysis.

**Table 1.** Generalized supermatrix (Feng et al., 2010)

	<i>Goal</i>	<i>Criteria</i>	<i>Sub-criteria</i>	<i>Alternatives</i>
Goal	1	...	...	...
Criteria	w <sub>21</sub>	w <sub>22</sub>	...	...
Sub-criteria	...	w <sub>32</sub>	w <sub>33</sub>	...
Alternatives	...	...	w <sub>43</sub>	1

In order to test key parameters in a cash flow forecast and to determine sensitivity of the NPV of a project to the changes in these parameters, SA is mostly used. To improve the decision-making process, combination of other tools makes this analysis more useful.

2.2.1. Net present value

A widely-used method of economical assessment of a project is NPV which becomes more extensive and also accepted as the measure of financial performance of a project. It simply calculates differences between present values of cash inflows and cash outflows. The capital value over time is considered during NPV. The value of capital in time is worth more than present in time future. Positive NPV relates to economic feasibility of project executed. Project with highest NPV gives the most preferable investment. NPV formula can be shown as below (Eq. 2):

$$NPV = -c_0 + \sum_{n=1}^N \left( \frac{PV_t}{(1+d)^t} + \frac{SV_N}{(1+d)^N} \right) \quad (2)$$

where:  $c_0$  is initial investment cost;  $N$  is project duration;  $PV_t$  is present value of cash flows in year  $t$ ;  $t$  is number of time periods;  $d$  is discount rate;  $SV_N$  is salvage value of the operating plant in  $N$ th year. NPV is specified for present value of benefits less present value of costs for energy projects.

The present computation of expenses is initial capital cost (ICC). It is considered that the dissemination of wind speed stays consistent which brings about uniform electricity production yield from year to year.

2.2.2. Internal rate of return

IRR is used as a method in order to calculate rate which makes net present value of investment zero. Investment is promoted only when the internal rate of return is higher than weighted average cost of capital. IRR is stated as most preferable evaluation method for investors in interviews because it expresses returns. IRR formula is given by Eq. (3):

$$IRR = \sum_{t=1}^t \frac{c_t}{(1+d)^t} - c_0 \quad (3)$$

where:  $t$  is number of time periods;  $c_t$  is net cash inflow during the period  $t$ ;  $d$  is discount rate;  $c_0$  is initial investment cost.

Although IRR is commonly used technique for evaluation of wind turbines, it has some drawbacks as de Oliveira and Fernandes (2013) stated below:

- Projects can have more than one IRR so that no clear decision can be made depending on the project cash flow structure.

- IRR assumes that cash flows can be reinvested at the IRR whereas NPV has a more realistic assumption for reinvestment which assumes that cash flows are reinvested in the defined discount rate.

- IRR does not consider the different sizes of investment which may still cause the absolute gain in wealth to be more different for the investor whereas NPV does not have this limitation.

3. Case study

There are three strategic criteria, namely, technical levels, economic aspects and environmental issues. There are criteria and sub-criteria defined in Table 2 under each strategic criterion. The five wind turbine systems under assessment are named as WTG1, WTG2, WTG3, WTG4, and WTG5 in order to keep anonymousness and their specifications are given in Table 3.

ANP method constructs a model of the problem organized into clusters comprising elements that are relevant to affect each other. DM determines the influence relations between model elements as per his own expertise. This is one of the most crucial phases of ANP method due to the challenge in identification of criteria that will affect others and relative density of it. ANP relations are listed in influence matrix as given in Table 4. In the matrix, 1 in position  $r_{ij}$  means that element in row  $i$  has impact on element of column  $j$ . The next step of ANP method includes establishment of impact density between the elements of network.

This influences the outcomes since all influences in which the alternatives participate would change if some of these alternatives changed. Table 5 shows related priorities of strategic criteria, criteria and sub-criteria.

Table 2. List of criteria levels

Strategic Criteria	Criteria	Sub-criteria
Technical levels (T)	- Turbine characteristics (T1) - Site profile (T2)	- Annual energy production (T11) - Rotor swept area (T12) - Annual mean wind speed (T21) - Capacity factor (T22)
Economical aspects (EC)	- Total expenditures (EC1) - Financials (EC2)	- Capital expenditures (EC11) - Operational expenditures (EC12) - Renewable energy tariff (EC21) - Discount rate (EC22)
Environmental issues (EN)	- Ecological impact (EN1) - Social welfare (EN2)	- Noise (EN11) - Land use (EN12) - Local employment (EN21) - Cultural disruption (EN22)

**Table 3.** Properties of five wind turbines

Wind turbine	WTG1	WTG2	WTG3	WTG4	WTG5
Rated power (MW)	3.0	3.0	3.3	3.0	3.2
Generator	Direct drive	Direct drive	Doubly fed asynchronous	Doubly fed asynchronous	Doubly fed asynchronous
Gearbox	Gearless	Gearless	Spur/planetary	Spur/2 x planetary	Spur/planetary
Voltage (V)	690	690	690	660	690
Hub height (HH) (m)	85	92	87	99	85
Rotor diameter (RD) (m)	113	115	126	131	130
Swept area (m <sup>2</sup> )	10000	10516	12469	13478	13273
Cut-in wind speed (m/s)	4	2	3	3	2
Cut-out wind speed (m/s)	25	25	22.5	25	25
Nominal wind speed (m/s)	12.5	11.5	12	11	12
Design life time (years)	20	20	20	20	20

**Table 4.** Influence matrix

Strategic criteria	Criteria	Sub-criteria	T				EC				EN				WTG				
			11	12	21	22	11	12	21	22	11	12	21	22	1	2	3	4	5
T	T1	T11				1					1				1	1	1	1	1
		T12	1			1	1	1			1	1			1	1	1	1	1
	T2	T21	1			1					1				1	1	1	1	1
		T22	1												1	1	1	1	1
EC	EC1	EC11	1	1		1		1			1	1	1	1	1	1	1	1	1
		EC12	1				1				1		1		1	1	1	1	1
	EC2	EC21					1								1	1	1	1	1
		EC22					1	1							1	1	1	1	1
EN	EN1	EN11												1	1	1	1	1	1
		EN12	1										1	1	1	1	1	1	1
	EN2	EN21						1							1	1	1	1	1
		EN22											1		1	1	1	1	1
WTG1			1	1	1	1	1	1	1	1	1	1	1						
WTG2			1	1	1	1	1	1	1	1	1	1	1						
WTG3			1	1	1	1	1	1	1	1	1	1	1						
WTG4			1	1	1	1	1	1	1	1	1	1	1						
WTG5			1	1	1	1	1	1	1	1	1	1	1						

Economic aspects (EC) with 0.454 priority factor is most crucial criterion, followed by technical levels (T), with 0.423 priority factor.

Sub-criteria priorities under same strategic criterion level can also be compared like under economic aspects (EC) criterion, most crucial sub-criterion, out of four sub-criteria in total, is capital expenditures (CAPEX), with 0.680 priority factor which means that major economic issue for selecting wind turbines is CAPEX of the project. Other sub-criteria are annual mean wind speed (0.669) and discount rate (0.636) respectively. Integrated priorities of sub-criteria and their respective rankings are also shown in Table 5. In-between all factors, CAPEX (EC11), with 0.128 integrated priority factor in network, is most critical item in wind turbine selection. Other main factors are annual mean wind speed (T21), discount rate (EC22), land use (EN12), and local employment (EN21).

**4. Results and discussion**

*4.1. Sensitivity analysis*

SA studies the change in the output of a model which may be divided to different sources and

belonging to the input data. The findings of SA are particularly important to researchers who study on optimization of the wind energy at the market, plant and as well as the turbine levels. Chowdhury et al. (2012; 2013a, b) researched the sensitivity of the wind plant output obtained by performing the unrestricted layout optimization algorithm. Andrew et al. (2014) researched the objectives and constraints of optimization on wind turbine level. SA done in this study may support to decide the most powerful parameters for further advancement of such models.

A numerical experiment is conducted to show how the wind plant investment is impacted by chosen turbine models. SA shows how the impacts of main plant-scale parameters like CAPEX, annual mean wind speed or discount rate change considerably with chosen turbine models. The sensitivity of the wind plant is analysed with various turbine models. The results highlight how the sensitivities are different from each other belonging to certain parameters by showing that optimization improves or lowers the relative sensitivity indices.

*4.1.1. Capital expenditures*

If the CAPEX related to turbine prices increases or decreases, NPV and IRR change with

respect to the change in CAPEX. Base case values are in the column of Table 6 which shows zero change. These are the numbers which are paid for turbines. The tendency of NPV and IRR based on CAPEX were showed with the graphs in the below.

The IRR change in WTG1 model with 3.0 MW rated power, 113 m RD and 85 m HH between +200000 € and -200000 € is 1.25 %. The equal change in IRR is 15.13 % of initial IRR. Every equal increase or decrease of CAPEX as shown in Fig. 1 causes a decrease or increase in NPV value which is 28197000 €. The equal change in NPV is 0.1536 % of initial NPV of WTG1. The IRR change in WTG2 model with 3.0 MW rated power, 115 m RD and 85 m HH between +200000 € and -200000 € is 1.25 %. The equal change in IRR is 15.33 % of initial IRR. Every equal increase or decrease of CAPEX as shown in Fig. 2 causes a decrease or increase in NPV value which is 28197000 €. The equal change in NPV is 0.1616 % of initial NPV of WTG2. The IRR change in turbine WTG3 model with 3.3 MW rated power, 126 m RD and 87 m HH between +200000 € and -200000 € is 1.31 %. The equal change in IRR is 11.98 % of initial IRR. Every equal increase or decrease of CAPEX as shown in Fig. 3 causes a decrease or increase in NPV value which is 24880000 €.

The equal change in NPV is 0.0869 % of initial NPV of WTG3. The IRR change in turbine WTG4 model with 3.0 MW rated power, 131 m RD and 99 m HH between +200000 € and -200000 € is 1.28 %. The equal change in IRR is 13.34 % of initial IRR. Every equal increase or decrease of CAPEX as shown in Fig. 4 causes a decrease or increase in NPV value which is 28197000 €. The equal change in NPV is 0.0999 % of initial NPV of turbine WTG4. The IRR change in WTG5 model with 3.2 MW rated power, 130 m RD and 85 m HH between +200000 € and -200000 € is 1.41 %.

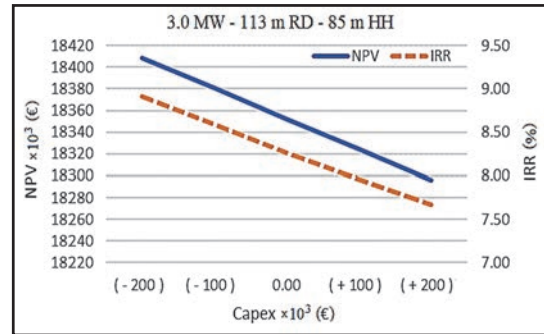


Fig. 1. Sensitivity graph of WTG1 due to capital expenditures

Table 5. Properties of criteria

Strategic criteria	Strategic priority	Criteria	Criteria priority	Sub-criteria	Sub-criteria priority	Integrated priorities	Integrated ranking
T	0.423	T1	0.444	T11	0.490	0.092	7
				T12	0.510	0.096	6
		T2	0.556	T21	0.669	0.126	2
				T22	0.331	0.062	11
EC	0.454	EC1	0.410	EC11	0.680	0.128	1
				EC12	0.320	0.060	12
		EC2	0.590	EC21	0.364	0.068	10
				EC22	0.636	0.119	3
EN	0.124	EN1	0.455	EN11	0.398	0.075	9
				EN12	0.602	0.113	4
		EN2	0.545	EN21	0.580	0.109	5
				EN22	0.420	0.079	8

Table 6. CBA due to capital expenditures

WTG type	Capital expenditures					
	CBA	- 200	- 100	0	100	200
WTG1	Price × 10 <sup>3</sup> (€)	2650	2750	2850	2950	3050
	NPV × 10 <sup>3</sup> (€)	18409	18381	18352	18324	18296
	IRR (%)	8.92	8.59	8.27	7.96	7.67
WTG2	Price × 10 <sup>3</sup> (€)	2600	2700	2800	2900	3000
	NPV × 10 <sup>3</sup> (€)	17510	17482	17454	17425	17397
	IRR (%)	8.78	8.45	8.13	7.82	7.53
WTG3	Price × 10 <sup>3</sup> (€)	2800	2900	3000	3100	3200
	NPV × 10 <sup>3</sup> (€)	28683	28658	28633	28608	28583
	IRR (%)	11.63	11.29	10.95	10.63	10.32
WTG4	Price × 10 <sup>3</sup> (€)	2700	2800	2900	3000	3100
	NPV × 10 <sup>3</sup> (€)	28279	28251	28223	28194	28166
	IRR (%)	10.23	9.89	9.57	9.26	8.95
WTG5	Price × 10 <sup>3</sup> (€)	2750	2850	2950	3050	3150
	NPV × 10 <sup>3</sup> (€)	30542	30516	30491	30465	30439
	IRR (%)	12.19	11.82	11.46	11.11	10.78

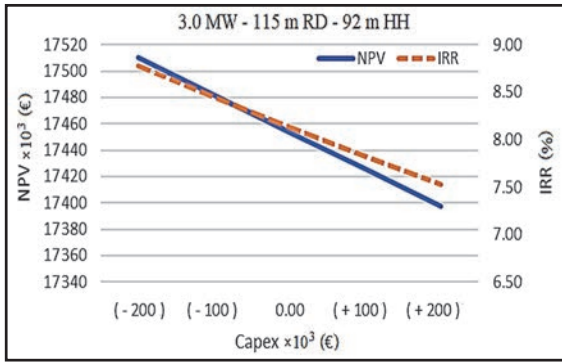


Fig. 2. Sensitivity graph of WTG2 due to capital expenditures

The equal change in IRR is 12.33 % of initial IRR. Every equal increase or decrease in CAPEX as shown in Fig. 5 causes a decrease or increase in NPV value which is 25917000 €. The equal change in NPV is 0.085 % of initial NPV of WTG5.

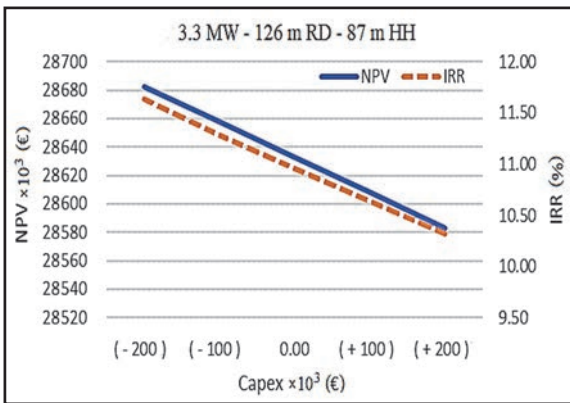


Fig. 3. Sensitivity graph of WTG3 due to capital expenditures

To sum up, turbines 1 and 2 have same decrease or increase in their NPV. When the change in NPV is taken % of initial NPV, the WTG1 and WTG2 show higher sensitivity than others. Again, if the change in IRR is taken % of initial IRR, the WTG1 and WTG2 show higher sensitivity than others. Turbine prices have higher impact on turbine WTG1 and WTG2.

4.1.2. Annual mean wind speed

AEP calculations in Table 7 are for all turbines in the wind farm based on turbine model. There will be 13 turbines in the plant. If wind speed of plant changes; annual energy yield of turbine models changes according to the turbine’s technological factors. The AEP values are calculated with WindPro program based on Weibull distribution. Discount rate was taken 9 % while calculating NPV and IRR values.

According to change in wind speed shown in Fig. 6, the IRR of WTG1 model with 3.0 MW rated power, 113 m RD and 85 m HH ranges between 5 % and 11 %. The IRR change shows rapid increase between the range of 6 m/s and 6.5 m/s, 6.5 m/s and

6.7 m/s, and 7 m/s and 7.5 m/s. IRR value of WTG1 model shows the highest increase between 6.5 m/s and 6.7 m/s.

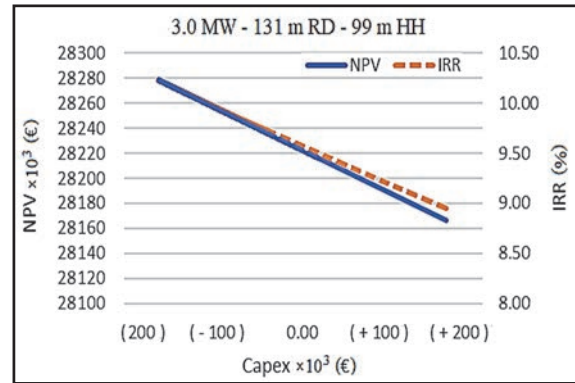


Fig. 4. Sensitivity graph of WTG4 due to capital expenditures

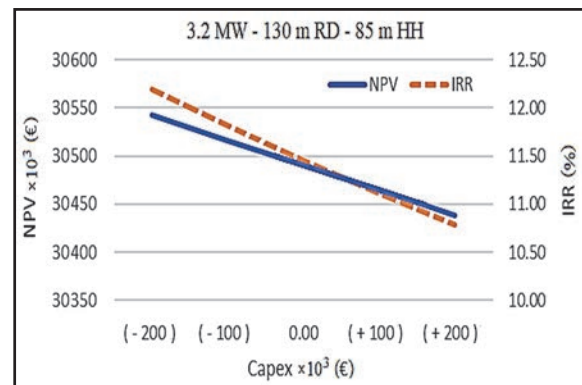


Fig. 5. Sensitivity graph of WTG5 due to capital expenditures

If wind speed increases from 6 m/s to 7.5 m/s, the NPV of turbine WTG1 becomes 12.42 times of the NPV while the wind speed is 6 m/s. In terms of range in wind speed and increase in NPV, it shows the highest increase between 6.5 m/s and 6.7 m/s and the lowest increase between 6.7 m/s and 7 m/s. So, WTG1 shows higher sensitivity in the range of 6.5 m/s and 6.7 m/s.

According to change in wind speed shown in Fig. 7, the IRR of WTG2 model with 3.0 MW rated power, 115 m RD and 85 m HH ranges between 5 % and 11 %. The IRR change shows rapid increase between the range of 6 m/s and 6.5 m/s, 6.5 m/s and 6.7 m/s, and 7 m/s and 7.5 m/s. IRR value of WTG2 shows the highest increase between 6.5 m/s and 6.7 m/s. If wind speed increases from 6 m/s to 7.5 m/s, the NPV of WTG2 becomes 20.83 times of the NPV while the wind speed is 6 m/s. In terms of range in wind speed and increase in NPV, it shows the highest increase between 6.5 m/s and 6.7 m/s and the lowest increase between 6.7 m/s and 7 m/s. So, WTG2 shows higher sensitivity in the range of 6.5 m/s and 6.7 m/s.

According to change in wind speed shown in Fig. 8, the IRR of WTG3 model with 3.3 MW rated power, 126 m RD and 87 m HH ranges between 7 %

and 14 %. The IRR change shows rapid increase between the range of 6 m/s and 6.5 m/s, 6.5 m/s and 6.7 m/s, and 7 m/s and 7.5 m/s. IRR value of WTG3 shows the highest increase between 6.5 m/s and 6.7 m/s. If wind speed increases from 6 m/s to 7.5 m/s, the NPV of WTG3 becomes 4.22 times of the NPV while

the wind speed is 6 m/s. In terms of range in wind speed and increase in NPV, it shows the highest increase between 6.5 m/s and 6.7 m/s and the lowest increase between 6.7 m/s and 7 m/s. So, turbine WTG3 shows higher sensitivity in the range of 6.5 m/s and 6.7 m/s.

Table 7. CBA due to annual mean wind speed

WTG type	Wind speed (m/s)					
	CBA	6	6.5	6.7	7	7.5
WTG1	AEP (MWh/year)	94756	109433	118697	125022	141194
	NPV × 10 <sup>3</sup> (€)	2664	12282	18352	22497	33094
	IRR (%)	5.10	7.08	8.27	9.05	10.98
WTG2	AEP (MWh/year)	93038	107927	117304	123698	140020
	NPV × 10 <sup>3</sup> (€)	1552	11309	17454	21644	32339
	IRR (%)	4.89	6.92	8.13	8.93	10.89
WTG3	AEP (MWh/year)	105996	122829	133224	140635	159013
	NPV × 10 <sup>3</sup> (€)	10791	21821	28633	33489	45532
	IRR (%)	7.44	9.65	10.95	11.86	14.04
WTG4	AEP (MWh/year)	106655	123418	133781	140762	158267
	NPV × 10 <sup>3</sup> (€)	10447	21432	28223	32027	44268
	IRR (%)	6.25	8.34	9.57	10.86	12.32
WTG5	AEP (MWh/year)	109019	125605	135979	143021	160882
	NPV × 10 <sup>3</sup> (€)	12824	23693	30491	35105	46809
	IRR (%)	8.00	10.16	11.46	12.32	14.44

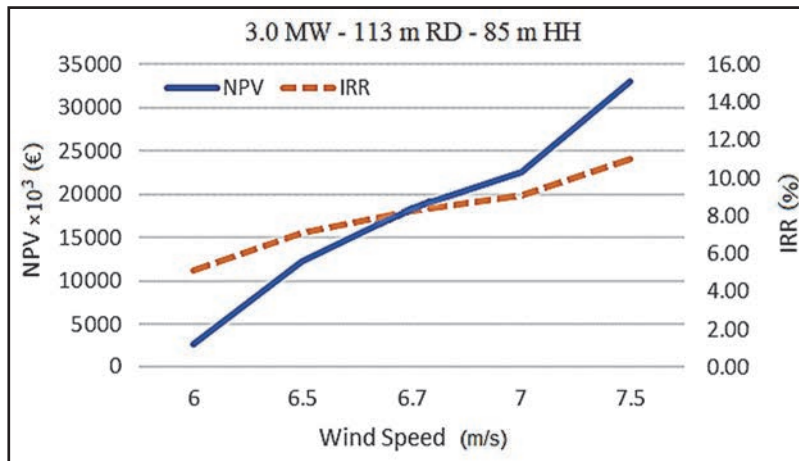


Fig. 6. Sensitivity graph of WTG1 due to annual mean wind speed

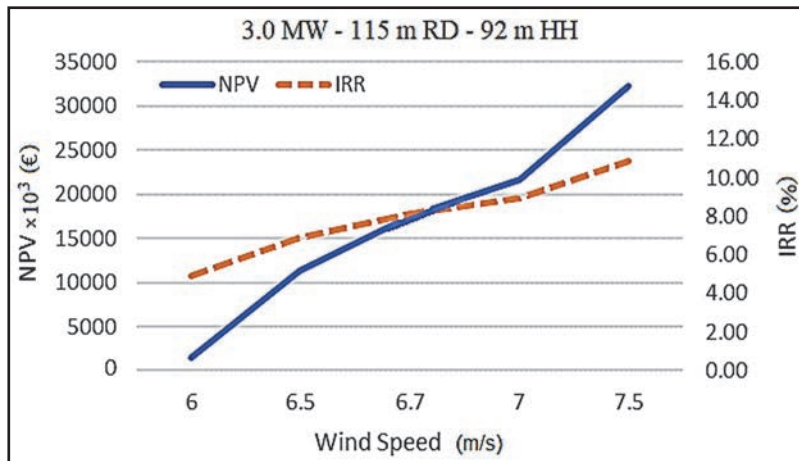


Fig. 7. Sensitivity graph of WTG2 due to annual mean wind speed

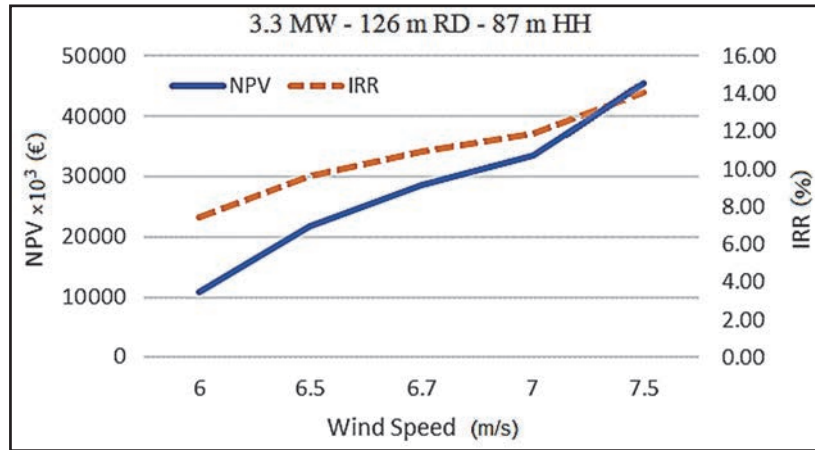


Fig. 8. Sensitivity graph of WTG3 due to annual mean wind speed

According to change in wind speed shown in Fig. 9, the IRR of WTG4 model with 3.0 MW rated power, 131 m RD and 99 m HH ranges between 6 % and 12 %. The IRR change shows rapid increase between the range of 6 m/s and 6.5 m/s, 6.5 m/s and 6.7 m/s, and 7 m/s and 7.5 m/s. IRR value of WTG4 shows the highest increase between 6.5 m/s and 6.7 m/s. In contrast to other turbine models, the wind speed change from 6.7 m/s to 7 m/s does not change the annual energy production. There is no impact on AEP between the wind speed range of 6.7 m/s and 7 km. Besides, the increase tendency of IRR between 7 m/s and 7.5 m/s is higher than other turbine models' tendency of this wind speed range.

If wind speed increases from 6 m/s to 7.5 m/s, the NPV of WTG4 becomes 4.24 times of the NPV while the wind speed is 6 m/s. In terms of range in wind speed and increase in NPV, it shows the highest increase between 6.5 m/s and there is no change in NPV between 6.7 m/s and 7 m/s. So, WTG4 shows higher sensitivity in the range of 6.7 m/s and 7 m/s. The increase tendency in NPV between 7 m/s and 7.5 m/s is very close to the increase tendency between 6.5 m/s and 6.7 m/s and shows more rapid increase than other turbine models in this wind speed range.

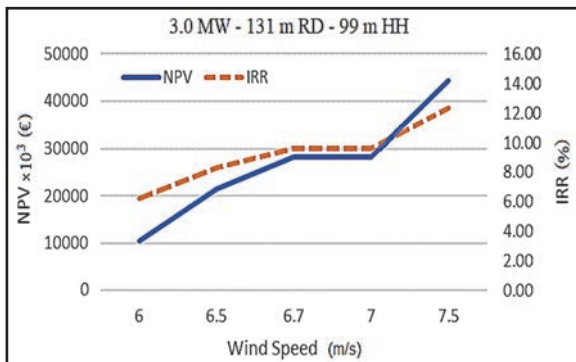


Fig. 9. Sensitivity graph of WTG4 due to annual mean wind speed

According to change in wind speed shown in Fig. 10, the IRR of WTG5 model with 3.2 MW rated power, 130 m RD and 85 m HH ranges between 8 % and 14 %.

The IRR change shows rapid increase between the range of 6 m/s and 6.5 m/s, 6.5 m/s and 6.7 m/s, and 7 m/s and 7.5 m/s. IRR value of WTG 5 shows the highest increase between 6.5 m/s and 6.7 m/s. If wind speed increases from 6 m/s to 7.5 m/s, the NPV of WTG5 becomes 3.65 times of the NPV while the wind speed is 6 m/s. In terms of the range in wind speed and the increase in NPV, it shows the highest increase between 6.5 m/s and 6.7 m/s and the lowest increase between 6.7 m/s and 7 m/s. So, WTG5 shows higher sensitivity in the range of 6.5 m/s and 6.7 m/s.

To summarize, all turbine models show higher sensitivity between 6.5 m/s and 6.7 m/s. The NPVs of WTG1 and WTG2 are highly correlated with wind speed changes. Their NPV increases rapidly depending on the increase in wind speed values. If wind speed increases in the wind farm are expected, these turbine models' correlations with wind speed should be considered. The increase tendency of WTG3 depending on wind speed ranges has higher impact on IRR and NPV than other turbine models. The wind speed change between 6.7 m/s and 7 m/s has no impact on turbine WTG4. There is no correlation between wind speed and NPV or IRR in this range. Wind speed has moderate impact on turbine WTG5. In comparison to NPV and IRR changes of other turbine models depending on wind speed, the NPV and IRR of turbine WTG5 increases less.

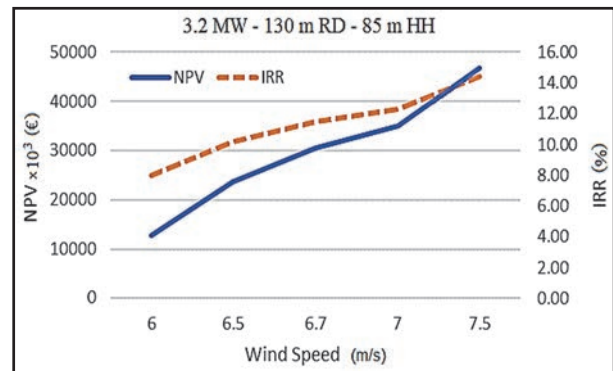


Fig. 10. Sensitivity graph of WTG5 due to annual mean wind speed



4.1.3. Discount rate

As per taken discount rate values in between 7 % and 11 %, the calculated NPV and IRR values of turbine models are given in Table 8.

The maximum and minimum IRR range in the below graphs is taken 0.5 % and NPV values are showed between 0 and 45 million Euros in the graphs.

Table 8. CBA due to discount rates

		Discount rate				
WTG type	CBA (%)	7	8	9	10	11
WTG1	NPV × 10 <sup>3</sup> (€)	29919	23781	18352	13534	9240
	IRR (%)	8.36	8.31	8.27	8.22	8.17
WTG2	NPV × 10 <sup>3</sup> (€)	28870	28111	17454	12698	8460
	IRR (%)	8.22	8.18	8.13	8.08	8.04
WTG3	NPV × 10 <sup>3</sup> (€)	41922	34869	28633	23098	18166
	IRR (%)	11.07	11.01	10.95	10.90	10.84
WTG4	NPV × 10 <sup>3</sup> (€)	41444	34427	28223	22715	17809
	IRR (%)	9.66	9.62	9.57	9.52	9.47
WTG5	NPV × 10 <sup>3</sup> (€)	44091	36873	30491	24826	19779
	IRR (%)	11.58	11.52	11.46	11.40	11.34

The changes in NPV and IRR values based on WTG1 model with 3.0 MW rated power, 113 m rotor diameter (RD) and 85 m hub height (HH) are shown in Fig. 11. When the linear trend line is added to both IRR and NPV functions, IRR trend function is  $y = -0.0005x + 0.0841$  and NPV trend function is  $y = -5E+06x + 3E+07$ .

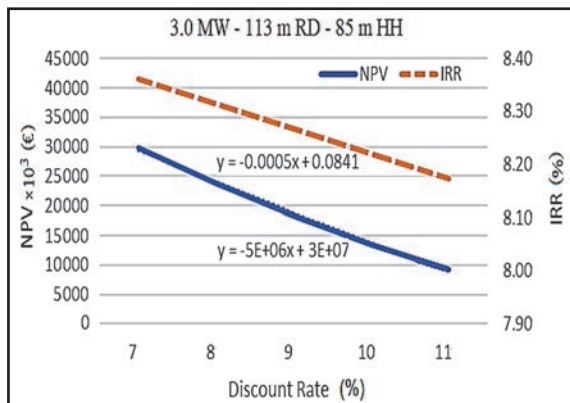


Fig. 11. Sensitivity graph of WTG1 due to discount rate

The changes in NPV and IRR values based on WTG2 model with 3.0 MW rated power, 115 m RD and 92 m HH are shown in Fig. 12. When the linear trend line is added to both IRR and NPV functions,

IRR trend function is  $y = -0.0005x + 0.0827$  and NPV trend function is  $y = -5E+06x + 3E+07$ .

The changes in NPV and IRR values based on WTG3 model with 3.3 MW rated power, 126 m RD and 87 m HH are shown in Fig. 13. When the linear trend line is added to both IRR and NPV functions, IRR trend function is  $y = -0.0006x + 0.1112$  and NPV trend function is  $y = -6E+06x + 5E+07$ .

The changes in NPV and IRR values based on WTG4 model with 3.0 MW rated power, 131 m RD and 99 m HH are shown in Fig. 14. When the linear trend line is added to both IRR and NPV functions, IRR trend function is  $y = -0.0005x + 0.0971$  and NPV trend function is  $y = -6E+06x + 5E+07$ .

The changes in NPV and IRR values based on WTG5 model with 3.2 MW rated power, 130 m RD and 85 m HH are shown in Fig. 15. When the linear trend line is added to both IRR and NPV functions, IRR trend function is  $y = -0.0006x + 0.1163$  and NPV trend function is  $y = -6E+06x + 5E+07$ .

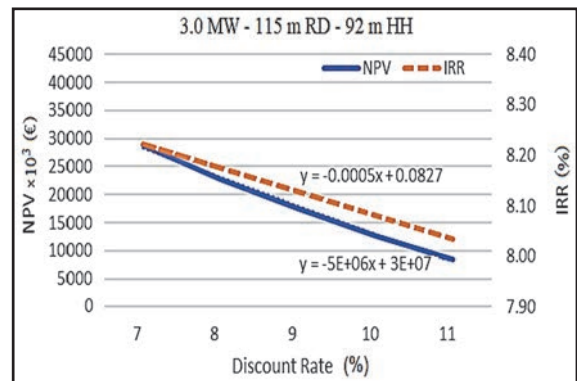


Fig. 12. Sensitivity graph of WTG2 due to discount rate

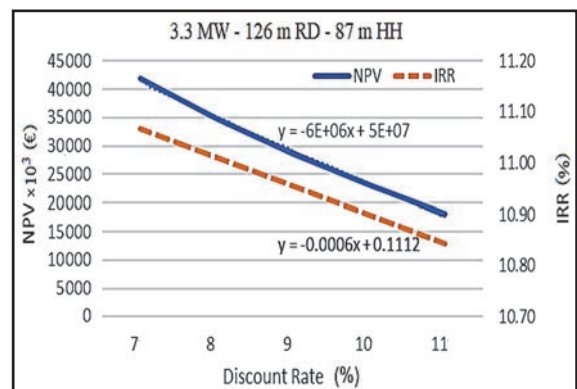


Fig. 13. Sensitivity graph of WTG3 due to discount rate

In simple linear regression, the equation of the model is  $y = b_0 + b_1x$ , where  $b_1$  is the coefficient of the x variable. The  $b_1$  coefficients give the direction of the relationship between discount rate and NPV or IRR values. If the  $b_1$  coefficient of the graphs is considered, all turbine models have a downward tendency with discount rate values. If discount rate increases, the NPV and IRR values of turbine models decrease. Turbine models 1, 2 and 4 have same  $b_1$  coefficient of IRR trend function. Turbine models 3 and 5 have higher  $b_1$  coefficient than other turbine models.

Turbine models 3 and 5 are more sensitive to the changes in discount rate. It causes to more decrease or increase in IRR value. More sensitivity in IRR change is risky for investors. This is not a preferred situation when analyzing the turbine models.

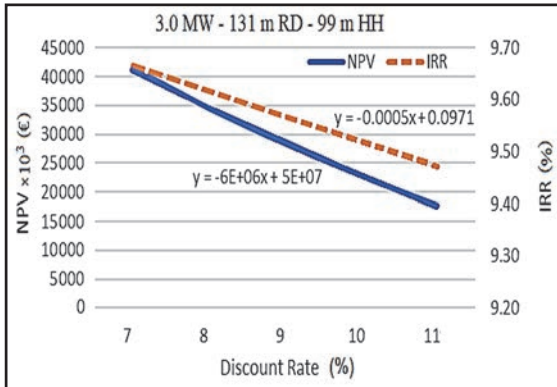


Fig. 14. Sensitivity graph of WTG4 due to discount rate

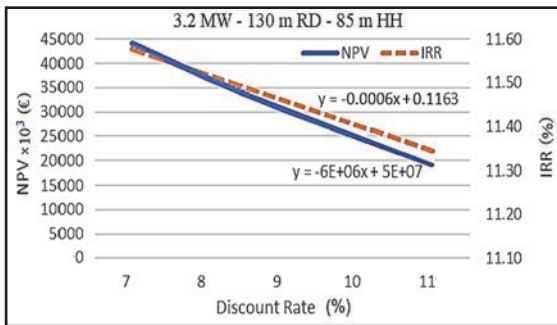


Fig. 15. Sensitivity graph of WTG5 due to discount rate

According to turbine model's NPV trend function,  $b_1$  coefficient of turbine models 1 and 2 has same value. Turbine models 3, 4 and 5 have higher value of  $b_1$  coefficient than turbine models 1 and 2. Turbine models 3, 4 and 5 are more sensitive to the changes in discount rate in terms of NPV values. It causes to more decrease or increase in NPV value. As in the IRR value evaluation, high sensitivity is not a preferred situation for investors.

When both IRR and NPV trend functions are examined, the turbine models 3 and 5 are riskier than others. In the determination of turbine models, the risk factor is also needed to be considered.

5. Conclusions

In this paper, an extensive assessment was done to comply with grid interconnection requirements of a given wind plant. The selection of most appropriate wind turbine technology is next critical point that requires involvement of multiple decision makers (DM) in the process after the wind plant location is decided. Since energy investment decisions are naturally multi-objective, conventional single-criterion decision-making is no more sufficient to solve the problem. In this study, a decision method in selection of most appropriate type of wind turbines is proposed.

The goal achievement factors are listed with a literature review first and then they are used to build network with four strategic criteria, namely, technical levels, economic aspects, financial schemes and environmental issues with various criteria and sub-criteria. By adopting ANP, the interrelationships between sub-criteria under each criterion are identified. MCDM method is used to determine the priority of criteria and sub-criteria and to evaluate overall wind turbine performance.

For the purpose of case study, 16 major non-technical and technical criteria were used to analyze optimal solution between 5 various alternatives of wind turbines for an onshore wind farm. SA is carried out to analyse the stability of method outputs to changes in parameter values. The use of ANP better shows the complication of problem. DM can compare the outputs of various WTGs and analyse their disadvantages and advantages, then should compare their outcomes with economic profitability analysis (i.e. CBA) of turbines to finally decide whether to select turbine WTG1, WTG2, WTG3, WTG4 or WTG5.

The application of ANP method especially in renewable energy applications can provide useful feedback for DM towards more accurate decisions. This method improves current decision-making procedure, providing more precise and scientific stability. Procedure proposed in this study contributes methodologically and conceptually to better understand complicated process of decision-making. DM can assess various scenarios by changing weights of criteria.

The most appropriate wind turbine models can be determined for construction of wind plant with application of this method. The method can also be adjusted as required to support evaluation of other renewable energy equipment and/or hybrid solutions which includes wind energy. The proposed method can be easily oriented and implemented by other wind plants in various locations or countries as reference when selecting most suitable wind turbines, although results may be case specific.

Future investigations should be implemented with more efficient and computational approaches to analyze the sensitivity of several turbine types. Since different cost models have different assumptions, a straightforward comparison may not yield comprehensive suitability simply by limiting scenarios of parameters ranked in this study. So, future work should investigate more complicated cases where cost model is implemented to its own assumptions.

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