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Two-stage multi-objective renewable energy optimisation

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Abstract

Energy use is paralleled with the need for renewable energy. Considering the abundance of wind potential in Turkey, it can be said that the advantages of wind energy are not sufficiently utilised. This study aims to determine the types and number of turbines to be used in the area where the wind farm will be established, with minimum cost. The facility was intended to be placed on both land and sea, and approaches were used to select a suitable coastal city. Since selection problems depend on more than one criterion in real life, the analytical network process, a multi-criteria decision-making technique, was used as a solution approach in this study. As a result of the model, it was decided to establish a wind turbine farm in Izmir. In the second phase of the study, the selected on-site settlement has been optimised. In this study, in which the appropriate site selection for heterogeneous wind farms and then field optimisation was made, turbine model selection, number and location are provided by a multi-objective mixed-integer optimisation model.

Keywords: ANP, energy, multi-criteria, renewable, wind;

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1. Introductıon

With the development of societies, it has become necessary to use energy in every field, but on the other hand, it has caused the rapid depletion of energy resources and a decrease in energy potential [1]. The fact that the decrease in the energy potential causes concern for the future of society accelerates the work carried out in this sector.

Renewable energy has a less negative impact on the environment than non-renewable energy sources since it produces minimal CO_2 emissions while generating electricity. The most important reasons for the widespread use of wind energy are that it has very low CO_2 emissions, low cost compared to other energy sources, is easy to install and has more variety. Considering the abundance of wind potential in Turkey, it can be said that the advantages of wind energy are not sufficiently utilised [2]. In Turkey, the location where the investment made by both the state and the private sector in wind energy should be made is a selection problem.

In real life, many decision problems are affected by more than one interactive criterion. For the establishment of a wind turbine farm, criteria such as ideal wind speed, physical structure, air density, altitude and slope are taken into consideration. Therefore, wind turbine farm site selection is also a multi-criteria decision-making problem [3]. Another problem focused on in the study is to determine the type and number of wind turbines to be placed in the selected site with a multi-purpose integer mathematical model.

1.1. Related studies

In the literature, AHP [3]– [7], analytical network process (ANP) [8], ELECTRE [4], [6] and multi-criteria decision-making (MCDM) methods, such as TOPSIS [9] and DEMATEL [8], were used. When the MCDM studies for the wind turbine site selection problem, which is one of the appropriate site selection problems, are examined, it is seen that there are relatively fewer studies than other site selection studies. With strong winds on the open seas, it is possible to produce 20%–30% more electricity than the offshore wind power plants used today. For this reason, the efficiency of wind power plants to be established on open seas is quite high. Ghosh [10] has proposed a new method to identify suitable places where the optimal amount of wave energy can be generated.

MCDM methods have been used in optimisation-oriented studies. An example of using a mathematical model for turbine model selection and placement is also found. Lee [11] developed critical success criteria in his study. Based on the MCDM method, AHP, a wind turbine project was selected by considering various criteria, such as the opportunities, costs and risks of the options.

In the study by Çayır [12], optimisation problems of the energy field are discussed and energy problems are classified according to the decision level, application area and energy type. The objectives of the models to be used in wind energy optimisation are mentioned. At the same time, Arı [13] focuses on the power plant site location selection, which is one of the most important issues in the establishment phase of the wind energy source. The site selection was carried out with two different perspectives and five different methods, namely MCDM methods and the linear programming model.

1.2. Purpose of the study

Since the wind turbine farm installation problem discussed in this study is a real-life problem with both qualitative and quantitative criteria and the relationships between its criteria, the ANP method, which takes into account the inter-metric dependency, was used. In line with these objectives, the study consists of two stages: site selection for the wind turbine farm to be established, selection of the appropriate turbine model, and mathematical modelling of the number of this turbine model selected. The first objective function is to minimise the cost; the second is to minimise the turbine brand and model used; and the third goal is to maximise the total produced power.

2. Materials and methods

One of the two main problems addressed in the study is the selection of the area where the wind turbine farm will be established. There are several criteria to consider while making this choice. However, not all of these criteria have the same degree of importance. It has been decided that the most efficient way to evaluate criteria of different importance in accordance with real life is ANP, one of the MCDM methods. The regression method was used to reduce the options at the stage of determining the city where the wind farm will be established with the ANP method.

Our other main problem is to determine the types and number of turbines to be used in the area where the wind farm will be established. While these were determined, it was aimed to minimise the cost and turbine model variety and to maximise the power to be produced. In line with the objectives, a multi-purpose mixed-integer optimisation model was created.

2.1. Analytical network process method

The ANP method, developed by Saaty [14], is the generalisation of the AHP method, which models decision problems with a finite number of options, the criteria and options that affect the decision, in a hierarchical order. If the criteria and options interact with each other, the decision model created to find the weights of all criteria and options has a network structure. As in the AHP method, both qualitative and quantitative criteria can be included in the decision model at the same time in the ANP method.

2.2. Mathematical optimisation model

Mathematical programming is examining or solving a problem by using values selected in a defined range in a function to optimise a function. The first studies on this subject are the publications made by Leontief to model the foreign trade and economic structure of the United States. Russian mathematician Kantorovich stated the need for optimisation in modern production systems in his article on modelling problems in production planning and methods with the best results.

3. Results

3.1. Analytical network process

The General Directorate of Meteorology and the Electrical Works Survey Administration have prepared the wind atlas of Turkey. The World Energy Agency has declared that if the wind speed is above 5.1 m/s, it shows the economy for wind power plants. As the first step, since the wind farm was intended to be established on land and sea, cities that do not have a coastline in Turkey were eliminated.

In the next stage, the wind speed classification of the cities was made based on the Turkey Wind Energy Potential Atlas published by the General Directorate of Energy Affairs. As a result of this classification, the provinces with the lowest speed were eliminated and the three provinces with the highest wind speed were selected.

Table 1. Cities with a wind speed greater than 5.1 m/s [15]

CITIES	Closed land	Open land	Shores	Offshore	Hills and slopes
Edirne		X	X	X	X
Kırklareli		X	X	X	X
Tekirdağ		X	X	X	X
Çanakkale	X	X	X	X	X
Balıkesir	X	X	X	X	X
İzmir		X	X	X	X
Aydın		X	X	X	X
Muğla		X	X	X	X
Antalya		X	X	X	X
Mersin		X	X	X	X
Adana		X	X	X	X
Hatay		X	X	X	X
Artvin				X	X
Rize				X	X
Trabzon				X	X
Giresun				X	X
Ordu				X	X
Samsun		X	X	X	X
Sinop		X	X	X	X
Kastamonu		X	X	X	X
Bartın	X	X	X	X	X
Zonguldak		X	X	X	X
Düzce		X	X	X	X
Sakarya		X	X	X	X
İzmit		X	X	X	X
İstanbul		X	X	X	X
Yalova		X	X	X	X
Bursa		X	X	X	X

In the next step, considering the data in Tables 1 and 2, five provinces with the highest efficiency (Kırklareli, Tekirdağ, İzmir, Muğla and Sakarya) were selected from the coastal provinces. Thus, we are left with eight provinces for which energy consumption forecasts for the next 5 years will be made.

Table 2. Energy uses and populations in 2018–2019 [16]–[19] (Türkiye Nüfusu. 2018–2019)

CITIES	The energy use of the province in 2018	The population of the province in	Individual energy use rate (2018)	Energy use of the province in 2019	Population of the province in 2019	Individual energy use rate (2019)

		2018				
Edirne	91.901,96	406.855	0,2259	88.702,25	411.528	0,2155
Kırklareli	176.065,38	356.050	0,4945	173.537,29	360.860	0,4809
Tekirdağ	563.680,99	1.005.000	0,5609	577.332,38	204.001	0,5605
Çanakkale	253.246,79	530.417	0,4774	204.539,66	540.662	0,3783
Balıkesir	309.553,09	1.205.000	0,2569	298.913,25	1.228.620	0,2433
İzmir	1.362.494,80	4.320.519	0,3154	1.274.024,79	4.367.000	0,2917
Aydın	219.833,34	1.081.000	0,2034	232.543,77	1.098.000	0,2118
Muğla	280.419,50	967.487	0,2898	302.626,39	967.487	0,3128
Antalya	603.384,51	2364000	0,2552	646.505,69	2.511.700	0,2574
Mersin	401.288,59	1.794.000	0,2237	404.863,71	1.840.425	0,2200
Adana	591.000,63	2.216.000	0,2667	589.635,21	1.769.000	0,3333
Hatay	400.522,23	1.575.000	0,2543	346.487,97	1.610.000	0,2152
Artvin	28.431,03	166.143	0,1711	35.615,65	174.010	0,2047
Rize	53.883,71	331.041	0,1628	50.753,90	348.608	0,1456
Trabzon	126.194,68	786.326	0,1605	131.605,81	808.974	0,1627
Giresun	56.895,87	437.393	0,1301	57.469,05	453.912	0,1266
Ordu	95.534,38	771.932	0,1238	103.040,19	771.932	0,1335
Samsun	221.071,04	1.313.000	0,1684	221.146,31	1.348.542	0,1640
Sinop	22.513,37	219.733	0,1025	32.014,18	219.733	0,1457
Kastamonu	71.250,28	372.373	0,1913	74.442,40	383.373	0,1942
Bartın	41.317,70	198.999	0,2076	35.944,71	198.999	0,1806
Zonguldak	109.043,07	596.892	0,1827	100.186,80	599.698	0,1671
Düzce	85.709,50	377.610	0,2270	80.717,58	387.844	0,2081
Sakarya	321.099,99	271.515	1,1826	279.475,39	276.385	1,0112
İzmit	827.029,89	1.883.000	0,4392	830.713,73	1.906.000	0,4358
İstanbul	3.747.476,51	15.067.724	0,2487	3.627.327,60	15.520.000	0,2337
Yalova	53.354,07	251.203	0,2124	65.258,25	262.234	0,2489
Bursa	1.019.962,31	2.937.000	0,3473	1.029.565,99	3.056.120	0,3369

The electricity consumption of the remaining eight provinces in the last 5 years has been estimated with the help of the SPSS programme until 2025. The suitable candidate cities (Tekirdağ, Balıkesir, İzmir and Sakarya) were selected for the wind turbine farm to be established on both land and sea, taking into account the graphics and the number of organised industrial zones (OIZ) in the provinces and the date presented in Table 3.

Table 3. Energy use and OIZ numbers of the last 5 years [20], [22]

CITIES	Energy use of the province in 2016	Energy use of the province in 2017	Energy use of the province in 2018	Energy use of the province in 2019	Energy use of the province in 2020	OIZ numbers
Kırklareli	171.415,79	133.740,95	176.065,38	173.537,29	170.919,20	4
Tekirdağ	518.174,33	491.888,68	563.680,99	577.332,38	621.162,28	13
Çanakkale	331.652,88	313.312,78	253.246,79	204.539,66	211.545,53	3
Balıkesir	324.409,62	281.737,92	309.553,09	298.913,25	303.948,91	8
İzmir	1.287.212,72	1.468.637,68	1.362.494,80	1.274.024,79	1.355.834,21	13
Muğla	253.533,88	268.477,99	280.419,50	302.626,39	254.666,24	1
Bartın	34.379,90	38.719,75	41.317,70	35.944,71	38.564,65	1
Sakarya	285.226,91	325.536,94	321.099,99	279.475,39	333.618,20	7

3.2. Determining the criteria

In order to determine the best candidate city in the ANP model, first of all, the criteria that will affect this decision were determined (Table 4). In the following stage, the relationships between the criteria and sub-criteria are explained.

Table 4. Criteria table

Main Criteria	Sub-criteria
	C_{11} Safe installation distance
Security	C_{12} Safety
C_1	C_{13} Regular plant tests
	C_{14} Information management
	C_{15} Natural disasters
	C_{21} Cost
Economy	C_{22} Reasonable power pricing
C_2	C_{23} Energy expenses
	C_{31} Employment
Social	C_{32} Social acceptance
	C_{33} Local benefits
C_3	C_{34} Tourism
	C_{41} Effect on living things and protection of ecology
Environment	C_{42} Land structure
C_4	C_{43} Distance
	C_{44} Noise
	C_{45} Aviation
Policy	C_{51} Energy subsidy policy
C_5	C_{52} Compliance with standards and regulations
	C_{61} Productivity
Technic	C_{62} Plant quality
C_6	C_{63} Spare parts in stock

C_1 Security: The installation of wind turbines in a safe zone prevents malfunctions that may occur during and after installation. The prediction of these failures and the selection of the installation according to these analyses also reduce the cost loss. After the main criterion was chosen as security, six sub-criteria were determined under this heading.

C_{11} Safe installation distance: In risky situations such as any malfunction or security problem that may occur within the wind farm, a safe distance should be left where the surrounding creatures will be least affected [8].

C_{15} Natural disasters: Taking into consideration lightning, landslide, avalanche, earthquake etc., it is vital to choose the land with the least risk of natural disaster [8].

C_2 Economy: One of the most important criteria for the new wind turbine field to be established is the economy. Things to consider minimising costs and achieve the greatest profit are explained with five sub-criteria under the heading of the economy.

C_{23} Energy expenses: Expenses of the facility, such as distribution and making energy available, excluding the cost items mentioned above [13].

C_3 Social: After the wind turbines are installed, the rate of use of the wind energy to be produced in this region is also very important. With the increasing demand, the benefits of renewable energy sources increase to a visible level. Four sub-criteria have been determined to affect this main criterion.

C_{32} Social acceptance: It is socially important that the establishment of a farm is accepted by the surrounding settlements [8], [13].

C_4 Environment: In every new project, it is necessary to minimise the negative situations that can affect living things. For this reason, the noise generated by the turbines to be installed should be minimised and should not be located in natural life protection areas. Based on all these, six sub-criteria that we determined play an important role in site selection are gathered under this main heading.

C_{45} Aviation: The glow emitted by turbines can have a negative impact on air traffic and navigation [24].

C_5 Policy: For the establishment of the farm, there are restrictions and regulations that must be followed by the state and some institutions/organisations. According to these constraints, three important sub-criteria were selected.

C_{52} Compliance with standards and regulations: The government clearly states its renewable energy policies, guidelines and installation. Alongside the framework set for the promotion and use of wind technology, the wind project encourages site selection [7], [8] .

C_6 Technical: Since establishing a wind farm is a costly investment, the highest efficiency should be obtained from the established field. The technical issues to be used in the site selection of the wind farm are divided into three sub-criteria.

C_{62} Plant quality: The material, land structure and workmanship selected during the establishment of the facility ensure sustainability. This increases the service life and reduces the cost of failure [8].

3.3. Model

After determining the main criteria and sub-criteria, Super Decision software was used to establish the ANP model. The options were created with the ANP model shown in Figure 1, taking into account the relationships between the main and sub-criteria.

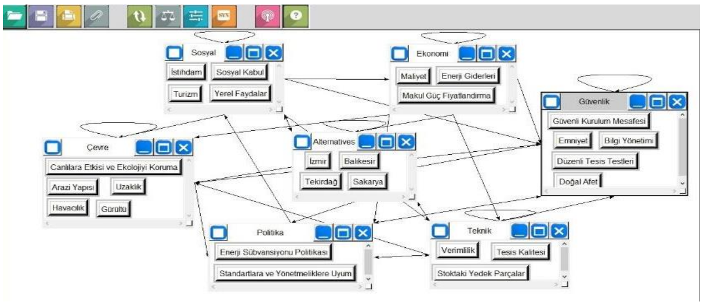

Figure 1. ANP model created in the programme

As an example of internal and external interactions, the relationships established for the province of Izmir are shown in Figure 2. The establishment of a wind farm in İzmir is affected by wind turbine power plants in Balıkesir, and under the safety sub-criterion, it is affected by safety and natural disasters.

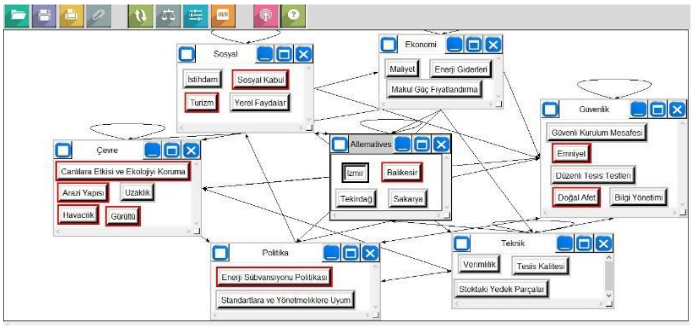

Figure 2. Relationships of the province of Izmir

After the model was created, pairwise comparisons were made by subject experts. Since there was more than one decision maker, the geometric average of the evaluations was taken. Different questions were asked in the evaluation of pairwise comparison matrices, as there are inter- and inter-cluster inter-criteria dependencies. Some of these questions are:

1. According to Balıkesir, how many times are the land structure, the impact on living things and the protection of ecology?
2. How many times more important is İzmir than Balıkesir, according to the energy expenditure criterion?
3. According to the cost criterion, how many times is a natural disaster more important than information management?

An example of pairwise comparison matrices is shown in Figure 3. For example, according to a decision maker and according to the energy expenditure criterion, İzmir province is four times more important than Balıkesir, five times more important than Sakarya and twice as important as Tekirdağ.

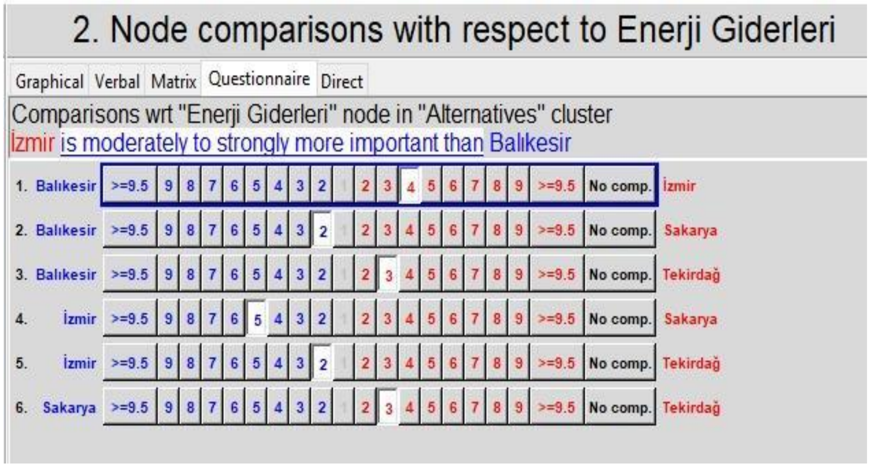

Figure 3. Pairwise comparison matrix of the question 'How many times more important is İzmir province than Balıkesir province according to the energy expenditure criterion?'

After all, pairwise comparisons were found to be consistent, and criterion and option weights were derived from the limit matrix. According to expert evaluations, the most suitable option for the installation of a wind turbine farm in our country was determined to be the province of İzmir. The weights of the candidate provinces are given in Table 5.

Table 5. The results of the ANP model created in the programme

Cities	Ideal	Normal	Raw
Balıkesir	0.572783	0.209880	0.005157
İzmir	1.000000	0.366422	0.009003
Sakarya	0.585154	0.214414	0.005268
Tekirdağ	0.571154	0.209284	0.005142

3.4. Mathematical optimisation model

After the site selection is made, a mixed-integer mathematical model has been established to minimise the cost and the number of turbine brands to be used and to maximise the power to be produced. In the established model, the *m* cluster represents the turbine brands, the *k* cluster represents the field will be on land or sea and the *t* cluster represents the turbine models.

Sets:

m = turbine brand index ($m = 1,2,3$)

k = field index ($k = 1,2$)

t = turbine model index ($t = 1,2,3,4$)

Decision variables:

x_{tmk} = on the field *k*, *m* brand's *t* number of models

y_{tmk} = {1, *m* brand's *t* number of models if *k* field is used; 0, dd}

Parameters:

B_m = number of turbine models in the brand *m*

c_{tmk} = on the field *k*, *m* brand's *t* cost of the model

v_k = average wind speed of the field *k*

g_{tm}= *m* brand's *t* sweeping area of the model

p_{tmk}= on the field *k*, *m* brand's *t* amount of power produced by the model

r_{tm} = *m* brand's *t* rotor diameter of the model

a_k = area of the field *k*

Formula for amount of power produced [24]

$$p_{ij} = (0{,}5) \cdot \rho \cdot v_k^3 \cdot C_p \cdot g_{tm}$$

ρ : air density (1.225 kg/m^3)

v_k^3: cube of the average wind speed of the field *k*

C_p : % of wind turbine efficiency (50%)

g_{tm}: *m* brand's *t* area swept by the model's wings

The area swept by the blades of the wind turbine = rotor radius * rotor radius * pi

Total cost formula [25]

$$c_{tmk} = x_{tmk} \left(\frac{2}{3} + \frac{1}{3} e^{-0.00174 x_{tmk}^2}\right)$$

Objective function of the model:

Z1 = $\sum_{t=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{2} x_{tmk} * c_{tmk} + \sum_{t=1}^{4}\sum_{m=1}^{3} y_{tmk}$

Z2 = $\sum_{t=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{2} x_{tmk} * p_{tmk}$

Enb [-Z1, Z2]

The mathematical model created aimed to maximise the power to be obtained from the turbines to be installed in the field and to minimise the cost and the number of turbine models to be used in the field.

Constraints of the model:

(1) $\sum_{t=1}^{4}\sum_{m=1}^{3} g_{tm} * x_{tmk} \leq a_k * f_{tmk} * y_{tmk}$ $\quad \forall_k \ (k = 1,2)$

(2) $\sum_{t}^{4} f_{tm1} * y_{tm1} \leq B_m$ $\quad \forall_m \ (m = 1,2,3)$

(3) $\sum_{t}^{4} f_{tm2} * y_{tm2} \leq B_m$ $\quad \forall_m \ (m = 1,2,3)$

(4) $\sum_{t=1}^{4}\sum_{m=1}^{3} f_{tmk} * y_{tmk} \geq 1$ $\quad \forall_k \ (k = 1,2)$

(5) $x_{tmk} \leq Mm_{tmk} * f_{tmk} * y_{tmk}$ $\quad \forall_m \ (m = 1,2,3), \forall_k \ (k = 1,2), \forall_t \ (t = 1,2,3,4)$

(6) $x_{tmk} \geq 0, \ y_{tmk} \epsilon \{0,1\}$ $\quad \forall_m \ (m = 1,2,3), \forall_k \ (k = 1,2), \forall_t \ (t = 1,2,3,4)$

In constraint number (1), it is ensured that the total area obtained by multiplying the swept areas of the selected turbines by the number of models selected for that site does not exceed the area of the site. f_{tmk} is the matrix offshore turbines expressed in the constraint and are installed in the open sea; land turbines are installed on land. Constraints (2) and (3) show how many turbine models from each brand can be used. Constraint (4) states that at least one turbine should be assigned to each site. While the constraint (5) Mm_{tmk} expresses the maximum values that the matrix and x_{tmk} variable can take. *k* and *m* on the field is a relationship constraint that requires the left side to be positive, although not necessarily, provided that the trademark is used. But the inverse inequality cannot be used because one of our goals is to minimise the number of turbine brands used. The constraint number (6) represents our sign constraints.

The created model was solved using the GAMS package programme in accordance with three purposes. The coded version of the model in the GAMS programme was transmitted with the project file.

4. Discussion

Heterogeneous wind farm site selection and optimisation have been studied to increase the potential of Turkey's use of renewable energy resources [26]. The criteria and alternatives required for WPP site selection and installation were determined as a result of the articles and theses examined. By using the ANP method, one of the MCDM methods that have been proven to be suitable for real life, it was determined that the candidate city that provided optimisation in terms of compliance with the criteria was İzmir.

In order to contribute to the literature, an optimisation model has been created in such a way that wind turbines are suitable for both onshore and offshore installation. In this model, while the cost and the wind turbine model used are tried to be minimised, it is aimed to maximise the power produced.

The outputs obtained by solving the multi-objective mixed-integer optimisation model created by using the three brands most suitable for the purpose of the study and four wind turbine models of each are shown in Table 6. The fact that all three objectives of the model have different units and different problem classes enabled the best solution to be obtained instead of the optimal result.

The results show that among the most suitable wind turbine brands and models used for the model, 150 turbines in total for land and offshore fields are above the average when considering the currently installed sites in Turkey.

Table 6. Selected turbines

MODEL	KARAYA KURULACAK TÜRBİN SAYISI	AÇIK DENİZE KURULACAK TÜRBİN SAYISI
Nordex N117/3600 Delta	17	
Nordex N131/3900 Delta	21	
Nordex N90/2500		
Nordex N90 Offshore		12
Vestas V112 Offshore		18
Vestas V112/3300	15	
Vestas V164/8000 Offshore		40
Vestas V164/8000		
Enercon E70/2300	6	
Enercon E-82 E4/2300	5	
Enercon E92/2350		
Enercon E112/4500		16
TOPLAM TÜRBİN SAYISI	64	86

Table 7 shows that the cost found by minimising the multi-purpose mathematical model is €2.585.674,000 and the turbine type is 9. The power it finds by maximising is 216,5944 MW. The obtained results were found by optimising the three objective functions.

Table 7. Objectives and consequences

AMAÇLAR	SONUÇ
Maliyetin enküçüklenmesi	€ 2.585.674.000
Türbin modeli sayısının enküçüklenmesi	9 adet
Üretilecek gücün enbüyüklenmesi	216,5944 MW

5. Conclusion

As a result of the literature research, the fact that the ANP method is not applied in the field selection problems, the use of the ANP method by showing a systematic approach for the field selection of the study shows its contribution to the literature. At the same time, the lack of an optimisation model for the field in the literature also indicates the contribution of this study to the literature.

In addition to using the optimisation model, examining both onshore and offshore areas for wind farm installation is another contribution of the study to the literature. The creation of an efficient and sustainable model of renewable energy sources is the most important contribution to the environment.

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