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TECHNO-ECONOMIC ASSESSMENT OF WIND ENERGY STORAGE TECHNOLOGIES VIA DECISION-MAKING MODELLING

Abstract:

Wind energy storage technologies should be improved by taking appropriate actions. However, all improvements increase the operational costs for the companies. Therefore, the most essential criteria should be identified to implement these actions efficiently. Accordingly, the purpose of this study is to understand the key issues for wind energy storage technologies. For this situation, a new model is established by using DEMATEL and TOPSIS techniques. Firstly, selected indicators are weighted via DEMATEL. Secondly, emerging seven economies are ranked with the help of TOPSIS. Hence, the main contribution of this study to the literature is that prior strategies can be identified for the improvements of the wind energy storage technologies by creating a new model. The results of this study can pave the way for the investors to increase the effectiveness of these projects. The findings indicate that technological development is the most critical issue for the performance improvements of the wind energy storage technologies. Durable materials and storage capacity are other critical factors for the development of these technologies. It is also stated that durable material is the most influencing factor since it affects all other criteria. On the other hand, storage capacity is the most influenced determinants because it is affected from all other items. In addition to them, it is also concluded that China is the most successful country with respect to the wind energy storage technology performance. Russia is another important emerging country in this framework.

Keywords:

Wind Energy; Energy Storage; Techno-economic Assessment

1. Introduction

Wind energy storage technologies are techniques in which the excess energy produced by wind turbines is stored to be used later when it is needed more. Due to its structure, wind energy can be negatively affected by climatic differences. In this context, more energy can be produced than needed when the wind is strong (Rekioua, 2023). Similarly, when the wind is low, the energy produced may not meet the needs. This situation can cause a huge problem especially for industrial manufacturers. Experiencing energy outages also causes disruptions in industrial production. This situation negatively affects both the financial performance of businesses and the growth of the country's economy (Gao et al., 2024). In summary, climatic changes can cause significant energy supply and demand imbalance for wind energy projects. To effectively combat this problem, excess produced energy needs to be stored.

The development of wind energy storage technologies is very important for increasing the performance of these projects. There are many different variables that affect the performance of these technologies. For example, for these technologies to be sustainable, *financial optimization* must be ensured (Boretti and Castelletto, 2024). Long-term use of technologies that are very costly is not possible. To achieve this goal, a comprehensive financial evaluation of these technologies is required (Pires et al., 2023). *Storage capacity* is another issue that affects the performance of these technologies. The efficiency of a technology that can store more can also be higher. This can be a very good solution for times when energy demand is very high (Adib et al., 2023). Otherwise, if sufficient energy is not stored, this problem cannot be solved successfully. This situation negatively affects the effectiveness of the wind energy storage technologies (Abdelghany et al., 2024).

The *charging and discharging rates* of the system are also necessary to increase the performance of wind energy storage technologies. This situation is directly related to the operating performance of energy storage technology (Walden et al., 2023). Thanks to the fast-charging time, storage technology can work actively for much longer. Thanks to this situation, it is possible to store more wind energy (Medghalchi and Taylan, 2023). If the charging process is too long, permanent disruptions may occur in the energy storage processes (Kluger et al., 2023). This situation negatively affects the efficiency of the projects. The *durability of the materials* used in energy storage processes is very important for the performance of these projects. Durable materials allow operational disruptions that may occur in the process to be minimized (Chojaa et al., 2023). This supports the implementation of energy storage processes more efficiently. When non-durable materials are used, disruptions may occur frequently in the storage processes (Giovanniello and Wu, 2023).

Adequate legal regulations also play a very important role in the development of wind energy storage technologies. The existence of these regulations is a source of assurance for both investors and consumers (Bedakhanian et al., 2024). Thus, interest in these projects is increasing even more (Pontes et al., 2023). On the other hand, investors' anxiety increases in countries with incomplete legal regulations. As a result, investors will be reluctant to invest in these projects. In addition, *technological development* is also of critical importance for wind energy storage technologies. One of the biggest advantages of using advanced technologies is the reduction of disruptions in the energy production process (Liu et al., 2024). This allows losses in the production process to be reduced (Zhu et al., 2023). Similarly, efficiency in operational processes can be increased by using advanced technologies. This allows businesses to manage their costs more successfully (El Mezdi et al., 2023).

There are many factors affecting the development of wind energy storage technologies. On the other hand, actions taken to improve these factors also lead to increased costs. Therefore, businesses cannot take many actions together to develop these technologies. The main reason for this is budget constraints, so excess costs cause financial problems for businesses. This situation makes the long-term continuity of the projects difficult. As a result, it is possible to identify the most important of these variables and take limited and effective actions. With the help of this issue, more effective strategies can be presented to the companies to increase the effectiveness of these investments. Therefore, the most important factors need to be determined. However, there are very few studies in the literature focusing on this subject. This is an important missing part for the wind energy storage literature.

Accordingly, the purpose of this study is to understand the key issues for wind energy storage technologies. For this situation, a new model is established by using DEMATEL and TOPSIS techniques. Firstly, selected indicators are weighted via DEMATEL. Secondly, emerging seven economies are ranked with the help of TOPSIS. Hence, the main contribution of this study to the literature is that prior strategies can be identified for the improvements of the wind energy storage technologies by creating a new model. The results of this study can pave the way for the investors to increase the effectiveness of these projects.

The following sections include analysis results and conclusion.

2. Analysis Results

A novel model is established to evaluation the performance of wind energy storage technologies. This model has two different sections. In the first stage, selected variables are weighted by the help of DEMATEL. This methodology is preferred by different researchers for various purposes (Kou et al., 2024; Eti et al., 2023). Secondly, emerging seven countries are ranked via TOPSIS technique. There are lots of studies in the literature in which TOPSIS model is taken into consideration (Erdebilli et al., 2023; Yüksel and Dinçer, 2023). The results of each stage are presented in the following subsections.

2.1. Computing the Weights of the Criteria

As a result of the literature review, six different criteria are determined that have an impact on the performance of the wind energy storage technologies. The details of these selected criteria are denoted in Table 1.

Table 1: Selected Criteria

Criteria	Codes
Financial optimization	FINOPT
Storage capacity	STOCAP
Charging and discharging rates	CHARAT
Durability of the materials	DURMAT
Adequate legal regulations	ADEREG
Technological development	TECDEV

In the following process, an expert team is constructed with three different people. The first two people are the top managers in international renewable energy companies. The third people is the professor of the energy finance. The questions are created with the criteria given in Table 1. After that, the experts make evaluations for these questions by using 5 different scales (0-no, 1-little, 2-normal, 3-influential, and 4-perfect). The details of the evaluations of the experts are denoted in Table 2.

Table 2: Evaluations for the Criteria

Expert 1						
Criteria	**FINOPT**	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
FINOPT	0	1	2	2	1	3
STOCAP	1	0	1	1	1	2
CHARAT	2	2	0	1	1	2
DURMAT	2	4	4	0	1	2
ADEREG	2	2	1	2	0	2
TECDEV	3	4	4	2	1	0
Expert 2						
Criteria	**FINOPT**	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
FINOPT	0	2	1	2	1	2
STOCAP	2	0	2	2	2	1
CHARAT	1	2	0	1	1	1
DURMAT	1	3	3	0	2	2
ADEREG	2	1	1	1	0	1
TECDEV	2	2	3	1	1	0
Expert 3						
Criteria	**FINOPT**	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
FINOPT	0	2	1	1	2	1
STOCAP	1	0	1	1	2	1
CHARAT	2	2	0	2	1	3
DURMAT	3	2	3	0	2	1
ADEREG	2	2	1	2	0	1
TECDEV	2	3	2	1	2	0

Direct relation matrix is generated in the following step. In this process, the average values of all experts are taken into consideration. Table 2 gives information about the direct relation matrix for the criteria.

Table 3: Direct Relation Matrix for the Criteria

Criteria	**FINOPT**	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
FINOPT	0.000	1.667	1.333	1.667	1.333	2.000
STOCAP	1.333	0.000	1.333	1.333	1.667	1.333
CHARAT	1.667	2.000	0.000	1.333	1.000	2.000
DURMAT	2.000	3.000	3.333	0.000	1.667	1.667
ADEREG	2.000	1.667	1.000	1.667	0.000	1.333
TECDEV	2.333	3.000	3.000	1.333	1.333	0.000

Normalized matrix is constructed in the following step. In this process, first the sum of each row in the direct relationship matrix is calculated. All values in the matrix are then divided by the largest row sum. As a result, a normalized matrix is obtained. The calculated normalized values are shown in Table 4.

Table 4: Normalized Matrix for the Criteria

Criteria	FINOPT	STOCAP	CHARAT	DURMAT	ADEREG	TECDEV
FINOPT	0.000	0.143	0.114	0.143	0.114	0.171
STOCAP	0.114	0.000	0.114	0.114	0.143	0.114
CHARAT	0.143	0.171	0.000	0.114	0.086	0.171
DURMAT	0.171	0.257	0.286	0.000	0.143	0.143
ADEREG	0.171	0.143	0.086	0.143	0.000	0.114
TECDEV	0.200	0.257	0.257	0.114	0.114	0.000

In the next process, total relation matrix is created. For this purpose, the formula of "(Normalized Matrix)*(Identity Matrix - Normalized Matrix)$^{-1}$" is taken into consideration. The details of the total relation matrix are indicated as follows.

Table 5: Total Relation Matrix for the Criteria

Criteria	FINOPT	STOCAP	CHARAT	DURMAT	ADEREG	TECDEV
FINOPT	0.386	0.586	0.515	0.439	0.406	0.502
STOCAP	0.440	0.401	0.458	0.378	0.391	0.413
CHARAT	0.505	0.602	0.405	0.413	0.380	0.499
DURMAT	0.662	0.826	0.778	0.423	0.533	0.605
ADEREG	0.513	0.560	0.468	0.425	0.290	0.440
TECDEV	0.654	0.791	0.725	0.503	0.488	0.454

The sums of the rows (SR) and columns (SC) are computed in the next section. In this process, "SR+SC" is used to compute the weights whereas "SR-SC" is considered to identify the causal directions. The details are indicated in Table 6.

Table 6: SR, SC and Weights of the Criteria

Criteria	SR	SC	SR-SC	SR+SC	Weights
FINOPT	2.8350	3.1605	-0.3255	5.9955	0.1642
STOCAP	2.4802	3.7654	-1.2852	6.2457	0.1710
CHARAT	2.8040	3.3487	-0.5447	6.1528	0.1685
DURMAT	3.8266	2.5815	1.2451	6.4081	0.1755
ADEREG	2.6975	2.4879	0.2096	5.1855	0.1420
TECDEV	3.6143	2.9136	0.7007	6.5279	0.1788

Table 6 gives information that technological development is the most critical issue for the performance improvements of the wind energy storage technologies since it has the highest weight (0.1788). Durable materials and storage capacity are other critical factors for the development of these technologies. Finally, the causal directions between these items are determined. In this process, the threshold value is identified. For this purpose, the average of all values in total relation matrix is computed. As a result, 0.507 is identified as the threshold value for this study. When a value higher than this value is found in the total relationship matrix, it means that the criterion on the left of the matrix affects the criterion above. As a result, the impact relation map between the criteria is shown in Figure 1.

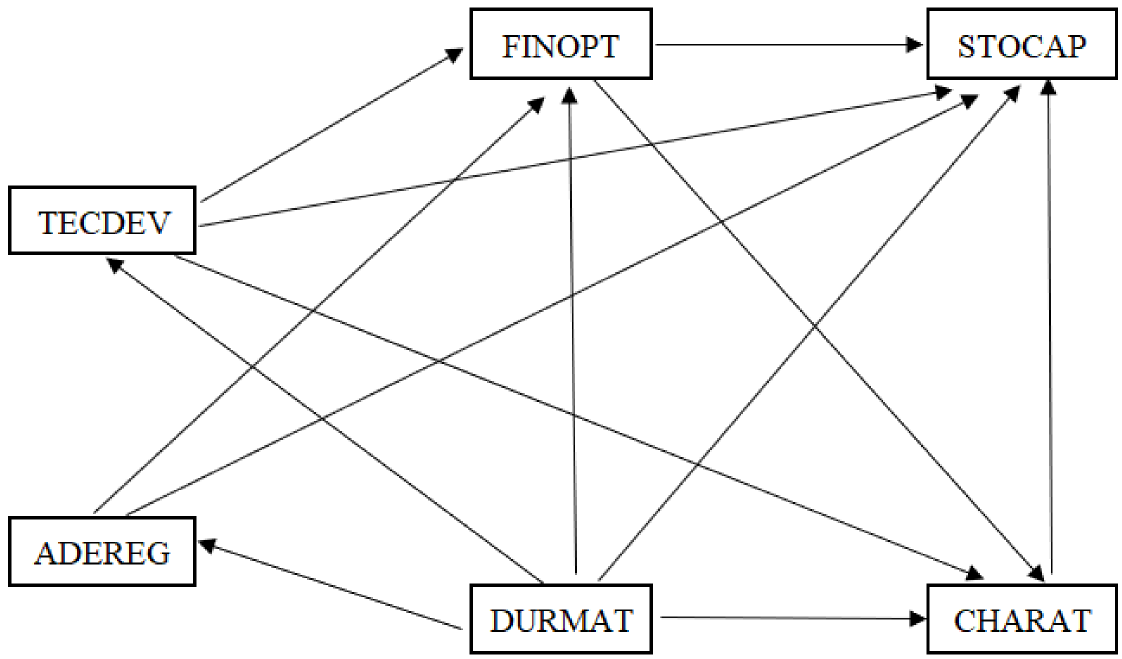

Figure 1: Impact Relation Map of the Criteria

Figure 1 explains that durable material is the most influencing factor since it affects all other criteria. On the other hand, storage capacity is the most influenced determinants because it is affected from all other items.

2.2. Ranking of Emerging 7 Countries

The second stage of the model is related to the ranking of emerging 7 countries with respect to the performance of wind energy storage technologies. In this context, five different scales are considered that are 1-poorest, 2-inadequate, 3-normal, 4-adequate, and 5-magnificent. The evaluations of the experts for the countries are shown in Table 7.

Table 7: Evaluations of the Experts for Countries

Expert 1						
	FINOPT	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
Brazil	2	1	2	2	2	1
China	5	5	4	4	5	4
India	2	1	1	2	1	1
Indonesia	1	1	1	1	2	1
Mexico	1	1	1	1	2	2
Russia	4	4	5	3	4	4
Turkey	2	2	1	2	2	1
Expert 1						
	FINOPT	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
Brazil	1	2	1	2	2	1
China	5	5	5	3	4	5
India	1	1	2	1	1	1
Indonesia	1	1	1	1	1	1
Mexico	1	2	1	1	1	2
Russia	3	3	4	3	3	3
Turkey	1	1	2	2	1	1
Expert 1						
	FINOPT	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
Brazil	1	1	2	1	2	1
China	5	5	5	5	5	4
India	2	2	1	1	1	1
Indonesia	1	2	2	1	1	1
Mexico	2	2	1	2	1	2
Russia	4	5	5	3	4	5
Turkey	1	2	1	1	2	1

In the following process, the average value of these evaluations is computed to create decision matrix. Table 8 underlines the details of this decision matrix.

Table 8: Decision Matrix for Countries

	FINOPT	**STOCAP**	**CHARAT**	**DURMAT**	**ADEREG**	**TECDEV**
Brazil	1.3333	1.3333	1.6667	1.6667	2.0000	1.0000
China	5.0000	5.0000	4.6667	4.0000	4.6667	4.3333
India	1.6667	1.3333	1.3333	1.3333	1.0000	1.0000
Indonesia	1.0000	1.3333	1.3333	1.0000	1.3333	1.0000
Mexico	1.3333	1.6667	1.0000	1.3333	1.3333	2.0000
Russia	3.6667	4.0000	4.6667	3.0000	3.6667	4.0000
Turkey	1.3333	1.6667	1.3333	1.6667	1.6667	1.0000

In the next step, this matrix is normalized. In this process, the sum of the squares of all alternatives related to that criterion is calculated and the square root of the result is taken. The normalization process is completed by dividing the existing value by this result. Table 9 gives information about the normalized matrix for the countries.

Table 9: Normalized Matrix for Countries

	FINOPT	STOCAP	CHARAT	DURMAT	ADEREG	TECDEV
Brazil	0.1933	0.1851	0.2297	0.2813	0.2931	0.1529
China	0.7251	0.6941	0.6430	0.6751	0.6839	0.6625
India	0.2417	0.1851	0.1837	0.2250	0.1466	0.1529
Indonesia	0.1450	0.1851	0.1837	0.1688	0.1954	0.1529
Mexico	0.1933	0.2314	0.1378	0.2250	0.1954	0.3058
Russia	0.5317	0.5553	0.6430	0.5063	0.5374	0.6116
Turkey	0.1933	0.2314	0.1837	0.2813	0.2443	0.1529

In the following step, the weighted normalized matrix is generated. In this process, the criteria weights in Table 6 are taken into consideration. Table 10 gives information about the values of weighted normalized matrix.

Table 10: Weighted Normalized Matrix for Countries

	FINOPT	STOCAP	CHARAT	DURMAT	ADEREG	TECDEV
Brazil	0.0317	0.0317	0.0387	0.0494	0.0416	0.0273
China	0.1190	0.1187	0.1084	0.1185	0.0971	0.1184
India	0.0397	0.0317	0.0310	0.0395	0.0208	0.0273
Indonesia	0.0238	0.0317	0.0310	0.0296	0.0278	0.0273
Mexico	0.0317	0.0396	0.0232	0.0395	0.0278	0.0547
Russia	0.0873	0.0950	0.1084	0.0888	0.0763	0.1093
Turkey	0.0317	0.0396	0.0310	0.0494	0.0347	0.0273

Positive and negative ideal solutions are identified in the next step. Within this framework, the highest value of all alternatives for each criterion is accepted as the positive ideal solution. On the other hand, the minimum value is defined as the negative ideal solution. Positive and negative ideal solutions are demonstrated in Table 11.

Table 11: Positive and Negative Ideal Solutions for Countries

	FINOPT	STOCAP	CHARAT	DURMAT	ADEREG	TECDEV
Positive Ideal Solutions	0.1190	0.1187	0.1084	0.1185	0.0971	0.1184
Negative Ideal Solutions	0.0238	0.0317	0.0232	0.0296	0.0208	0.0273

After this, distance values to ideal and non-ideal points are calculated. In this process, the square of the distance of each value from the ideal values is calculated. Then, the square root of the sum of each value is calculated. The distances to the positive and negative ideal solutions are shown in Table 12.

Table 12: The Distances to the Positive and Negative Ideal Solutions for Countries

	Distances to Positive Ideal Solution	Distances to Negative Ideal Solution
Brazil	0.1903	0.0336
China	0.0001	0.2143
India	0.2006	0.0203
Indonesia	0.2089	0.0104
Mexico	0.1904	0.0319
Russia	0.0544	0.1691
Turkey	0.1919	0.0277

Furthermore, the relativity closeness of the alternatives to the ideal solution is calculated. In this context, the formula "distance to negative ideal/(distance to negative ideal + distance to positive ideal)" is taken into consideration. Table 13 denotes the details of the relativity closeness of the alternatives to the ideal solutions.

Table 13: The Relativity Closeness to the Ideal Solutions for Countries

	The Relativity Closeness to the Ideal Solutions	Ranking Results
Brazil	0.15000919	3
China	0.99956078	1
India	0.09172757	6
Indonesia	0.04749185	7
Mexico	0.14366527	4
Russia	0.75659257	2
Turkey	0.12621579	5

The highest the relativity closeness to the ideal solution values gives information about the best alternatives. Hence, Table 13 defines that China is the most successful country with respect to the wind energy storage technology performance. Russia is another important emerging country in this framework. However, Turkey, India and Indonesia are the least successful countries in this context.

3. Conclusions

In this study, it is aimed to identify the key issues for wind energy storage technologies. Within this context, a new model is established by using DEMATEL and TOPSIS techniques. Firstly, selected indicators are weighted via DEMATEL. Secondly, emerging seven economies are ranked with the help of TOPSIS. Hence, the main contribution of this study to the literature is that prior strategies can be identified for the improvements of the wind energy storage technologies by creating a new model. The results of this study can pave the way for the investors to increase the effectiveness of these projects. The findings indicate that technological development is the most critical issue for the performance improvements of the wind energy storage technologies. Durable materials and storage capacity are other critical factors for the development of these technologies. It is also stated that durable material is the most influencing factor since it affects all other criteria. On the other hand, storage capacity is the most influenced determinants because it is affected from all other items. Additionally, it is also concluded that China is the most successful country with respect to the wind energy storage technology performance. Russia is another important emerging country in this framework.

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