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Pathways to Energy Independence: Spherical Fuzzy Modeling for Decision Making in Energy Investments

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ABSTRACT

The purpose of this study is to identify critical strategies to provide energy independence. In this scope, a new fuzzy decision-making model is created to answer this question. This model has two different stages. In the first stage, selected criteria are weighted with spherical fuzzy DEMATEL. In the following stage, seven different investment alternatives are identified by considering the details of the literature review results. These alternatives are ranked by spherical fuzzy SAW. The main contribution of this study is that effective strategies can be presented to obtain energy independence. With the help of this issue, the countries can focus on the most appropriate issues without having budget deficit. Moreover, considering DEMATEL methodology to weight the criteria provides some benefits. Owing to this issue, the causal relationship among the determinants can be identified. The most important criterion in energy independence is improving technological improvement. On the other side, the ranking results indicate that nuclear and solar energy are the most critical investment alternatives for energy independence.

Keywords: energy independence; energy investments; DEMATEL; SAW; spherical fuzzy sets

JEL Classification: C80, G21, O22

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1. INTRODUCTION

Energy independence means that a country can meet its energy needs from its own internal resources. This situation is both important and necessary for countries in many respects. Energy independence increases the security of a country's energy supply. Considering that a country is dependent on foreign sources of energy, it is understood that this country is also dependent on foreign energy (Dinçer et al., 2024). Therefore, there is a risk that the country will not be able to supply energy in case of a possible political problem. This situation negatively affects the industrial production and economic development of countries. On the other hand, countries dependent on energy imports are more affected by fluctuations in global energy prices (Liu et al., 2024). In this case, thanks to energy independence, countries can be more resilient to these shocks. This also contributes significantly to countries' economic stability. The effort to achieve energy independence directs countries to conduct research in areas such as energy technologies. Thus, the technology level in the country will advance, which allows businesses to increase their productivity (Eti et al., 2024).

There are many different strategies for the countries to provide energy independence. Nuclear energy is one alternative to achieve this objective. The main advantage of this energy type is the generation of the domestic energy for the countries (Kou et al., 2024). However, radioactive waste is the main drawback of these reactors. In addition to this issue, renewable energy projects also play a critical role to provide energy independence. Within this framework, solar, wind, geothermal, biomass and hydropower energy alternatives can be taken into consideration (Datsyuk et al., 2024). These energy alternatives have a powerful contribution to the carbon emission reduction. Nevertheless, renewable energy projects are affected from the climatic factors. This situation has a negative influence on the effectiveness of the electricity generation. In addition to this issue, renewable energy projects includes complex engineering process (Yüksel et al., 2024). This condition increases the difficulties in this process. Having fossil fuels increases energy independence, but this situation has negative impacts on the environment due to carbon emission (Aysan et al., 2024).

This study aims to identify critical strategies to provide energy independence. For this purpose, a new fuzzy decision-making model is created to answer this question. This model has two different stages. In the first stage, selected criteria are weighted with spherical fuzzy DEMATEL. In the following stage, seven different investment alternatives are identified by considering the details of the literature review results. These alternatives are ranked by spherical fuzzy SAW. The main contribution of this study is that effective strategies can be presented to obtain energy independence. With the help of this issue, the countries can focus on the most appropriate issues without having budget deficit. Moreover, considering DEMATEL methodology to weight the criteria provides some benefits. Owing to this issue, the causal relationship among the determinants can be identified.

The following section gives information about the literature review. Analysis results are shared in the third section. In the final part, conclusions are highlighted.

2. LITERATURE REVIEW

Countries around the world are implementing a number of regulations to reduce carbon emissions. In addition, countries are developing national energy strategies by turning to renewable resources to produce enough energy for themselves (Magnolia et al., 2023). One of the resources that can be utilized in line with national energy strategies is nuclear energy. Throughout history, many countries have shown interest in nuclear energy and resorted to this source for energy supply (Kim et al., 2024; Kartal and Pata, 2023). Nuclear energy is one of the important resources that countries have in energy independence. Zheng et al. (2024) states that nuclear energy production is a sustainable energy production solution. Ou et al. (2024) is of the opinion that the use of nuclear intensive electrical energy production in renewable energy production will contribute to energy independence. Housni et al. (2024) conducted an analysis on the use of nuclear energy to produce low-carbon energy in Morocco. After the analysis, they determined that the use of nuclear energy would increase energy independence.

Renewable energy constitutes one of the important criteria in ensuring energy independence. Development of renewable energy; It is seen as a result of environmental degradation and energy instability. For this reason, investments in this field are increasing and renewable energy sources are diversifying (Chu et al., 2023; Yüksel et al., 2023). Thanks to energy laws and government regulations, interest in renewable energy is also increasing (Liu and Feng, 2023). Hassan et al. (2024) state that renewable energy is important for global energy transformation. It also states that the adoption of renewable energy will make positive contributions to energy independence in countries. Huang et al. (2024) state that the use of microgrids is one of the beneficial applications in terms of energy independence. In addition, this method is important in terms of ensuring local resource use and environmental sustainability. However, Yadav and Mahalik (2024) state that the development of renewable energy will reduce dependence on energy imports in developing countries. Finally, Khan et al. (2024) plays an explanatory role in the energy security of renewable energy in their study. They also point out that there is a causal relationship between these two variables.

Sustainable economic growth has become one of the important concepts in the global competitive environment. Uninterrupted energy resources are needed to ensure sustainable economic growth (Eti et al., 2023). Importing energy from abroad creates an obstacle to providing uninterrupted energy. In this respect, countries need to turn to domestic energy sources (Emre, 2023). Addai et al. (2024) state that with the increase in urbanization, fossil fuel use increases in the Black Sea region. Maneejuk et al. (2024) is of the opinion that fluctuations in energy prices negatively affect energy importing countries. In order to be protected from these fluctuations, it is important for countries to switch to sources that will ensure energy independence.

3. FINDINGS

The study to obtain the most optimal alternative solution for energy independence is in two stages. In the first stage, effective criteria for energy independence are determined and weighted using the DEMATEL method (Özdemirci et al., 2023; Eti et al., 2023; Dinçer et al., 2023). The main reason for this is the assumption that there is interaction between the criteria and the lack of numerical measurements of the criteria (Martínez et al., 2023; Al-Binali et al., 2023). In the second stage of the study, the alternatives are ranked using the SAW method. Since both methods consider the linguistic evaluations of decision makers as data, spherical fuzzy numbers are used to analyze linguistic uncertainty. The results of the two stages are presented under subheadings.

3.1 Identification of Criteria and Alternatives for Energy Independence

Strategy alternatives applied for energy independence and effective criteria in the selection of these alternatives are determined as a result of literature analysis. Code equivalents and definitions of criteria in the analysis part of the study are presented in Table 1.

Table 1: Criteria Set

Definition	Code
Government Support	CR1
Technological Improvement	CR2
Qualified People	CR3
Organizational Effectiveness	CR4

The alternatives and their codes to be selected based on the criteria are shared in Table 2.

Table 2: Alternatives

Definition	Code
Nuclear	A1
Solar	A2
Wind	A3
Geothermal	A4
Biomass	A5
Hydropower	A6
Fossil Fuels	A7

3.2. Weighting of Criteria with Spherical Fuzzy DEMATEL

Effective criteria for energy independence are evaluated by three different decision makers using the linguistic terms in Table 3.

Table 3: Linguistic Terms

Terms	μ	v	π
S	.85	.15	.45
M	.6	.2	.35
W	.35	.25	.25
NI	0	.3	.15

The evaluations of the three decision makers in linguistic terms are summarized in Table 4.

Table 4: Evaluation of Decision Makers

	CR1	CR2	CR3	CR4
CR1	-, -, -	NI, S, S	NI, NI, S	S, S, M
CR2	S, S, S	-, -, -	NI, S, S	M, M, W
CR3	M, S, S	S, NI, NI	-, -, -	M, M, S
CR4	W, M, M	W, W, W	S, S, S	-, -, -

Spherical fuzzy number equivalents of the linguistic terms in Table 4 are used for analysis. By calculating the spherical fuzzy arithmetic mean of the decision makers' evaluations, the direct relationship matrix is obtained. The direct relationship matrix is given in Table 5.

Table 5: The Direct Relationship Matrix

	CR1			CR2			CR3			CR4		
CR1	.000	.000	.000	.758	.189	.499	.590	.238	.487	.796	.165	.473
CR2	.850	.150	.450	.000	.000	.000	.758	.189	.499	.538	.215	.330
CR3	.796	.165	.473	.590	.238	.487	.000	.000	.000	.718	.182	.461
CR4	.538	.215	.330	.350	.250	.250	.850	.150	.450	.000	.000	.000

The direct relationship matrix is divided into three submatrices according to the components of the spherical fuzzy number. Then, the normalization process is applied for all three submatrices. In the normalization process, the largest sum of row and column elements is calculated and then all elements are divided by this value. Normalized submatrices are given in Table 6.

Table 6: The Normalized Matrix

μ	CR1	CR2	CR3	CR4
CR1	.000	.345	.268	.362
CR2	.387	.000	.345	.245
CR3	.362	.268	.000	.327
CR4	.245	.159	.387	.000
v	**CR1**	**CR2**	**CR3**	**CR4**
CR1	.000	.279	.352	.244
CR2	.222	.000	.279	.318
CR3	.244	.352	.000	.268
CR4	.318	.369	.222	.000
π	**CR1**	**CR2**	**CR3**	**CR4**
CR1	.000	.342	.334	.324
CR2	.308	.000	.342	.226
CR3	.324	.334	.000	.316
CR4	.226	.171	.308	.000

Then, the total relationship matrix is calculated. To calculate the total relationship matrix, the normalized matrix is subtracted from the identity matrix and its inverse is taken. The normalized matrix is multiplied by the inverted matrix. This process is applied for three sub normalized submatrices. Finally, Euclidean normalization is performed. Spherical fuzzy total relationship matrix is shared in Table 7.

Table 7: Spherical Fuzzy Total Relationship Matrix

	CR1			CR2			CR3			CR4		
CR1	.488	.449	.499	.536	.510	.561	.521	.533	.555	.530	.513	.556
CR2	.538	.490	.516	.495	.428	.456	.534	.496	.514	.525	.507	.500
CR3	.523	.511	.550	.522	.517	.550	.482	.444	.489	.521	.514	.545
CR4	.446	.545	.427	.442	.538	.418	.459	.521	.434	.415	.464	.380

The row (R) and column (C) totals of the matrix in Table 7 are obtained and the totals are defuzzified. The results are shown in Table 8.

Table 8: R and C Values

	R	C
CR1	1.126	1.230
CR2	1.120	1.323
CR3	1.124	1.181
CR4	1.124	0.826

Criterion weights and rankings are determined based on the sum of R and C values. The importance weights and rankings of the criteria are given in Figure 1.

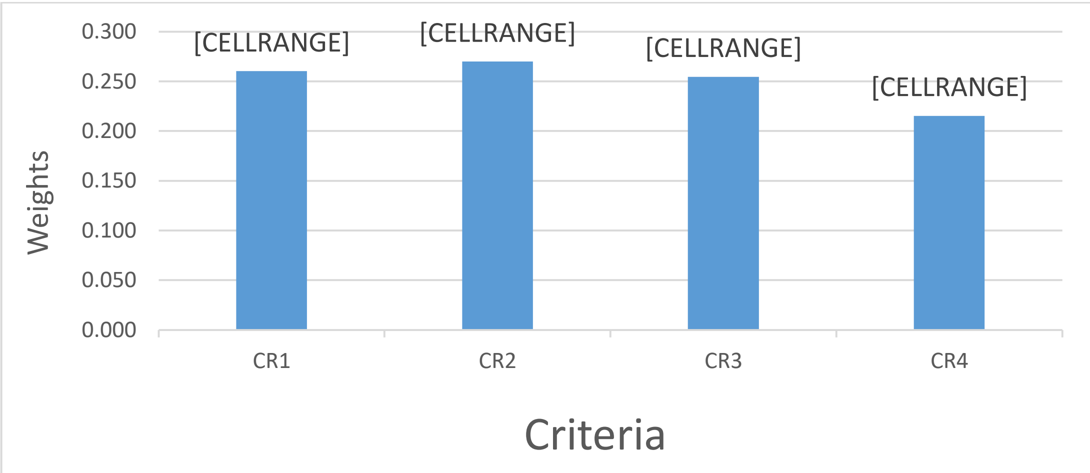

Figure 1: Weights of Criteria

According to Figure 1, the most important criterion in energy independence is improving technological improvement and its importance weight is 0.27. Government support ranks second for energy independence with an importance weight of 0.26. Organizational effectiveness ranks last among the criteria for energy independence. The importance weight of this criterion is 0.215.

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3.3. Ranking of Alternative Strategies for Energy Independence Using Spherical Fuzzy SAW

The linguistic scale used by decision makers to rank the alternatives is given in Table 9.

Table 9: Linguistic Scale for Ranking

Scale	μ	v	π
AMI	.9	.1	.1
VHI	.8	.2	.2
HI	.7	.3	.3
SMI	.6	.4	.4
EI	.5	.5	.5
SLI	.4	.6	.4
LI	.3	.7	.3
VLI	.2	.8	.2
ALI	.1	.9	.1

Using linguistic terms, evaluations collected from three different decision makers are shared in Table 10.

Table 10: Evaluations of Alternatives

	CR1	CR2	CR3	CR4
A1	AMI, AMI, AMI	AMI, AMI, AMI	VHI, VHI, VHI	SMI, SMI, SMI
A2	VHI, VHI, VHI	VLI, LI, VLI	VHI, AMI, VHI	VHI, VHI, VHI
A3	HI, HI, HI	HI, HI, HI	HI, HI, HI	HI, HI, HI
A4	EI, LI, LI	EI, EI, EI	EI, LI, LI	EI, EI, EI
A5	VLI, VLI, VLI	EI, EI, EI	VHI, VHI, VHI	VLI, VLI, VLI
A6	SLI, SLI, AMI	SLI, SMI, SMI	SLI, SLI, SLI	VLI, VLI, VLI
A7	HI, HI, HI	HI, HI, VHI	HI, SMI, HI	HI, HI, VHI

The spherical fuzzy decision matrix is obtained by taking the arithmetic mean of the spherical fuzzy number responses of the decision makers. The Spherical Fuzzy decision matrix is exhibited in Table 11.

Table 11: Spherical Fuzzy Decision Matrix

	CR1			CR2			CR3			CR4		
A1	.900	.100	.100	.900	.100	.100	.800	.200	.200	.600	.400	.400
A2	.800	.200	.200	.239	.765	.240	.842	.159	.164	.800	.200	.200
A3	.700	.300	.300	.700	.300	.300	.700	.300	.300	.700	.300	.300
A4	.383	.626	.397	.500	.500	.500	.383	.626	.397	.500	.500	.500
A5	.200	.800	.200	.500	.500	.500	.800	.200	.200	.200	.800	.200
A6	.699	.330	.274	.547	.458	.402	.400	.600	.400	.200	.800	.200
A7	.700	.300	.300	.739	.262	.266	.671	.330	.333	.739	.262	.266

By multiplying the decision matrix criterion weights, the weighted spherical fuzzy decision matrix is calculated. The criterion weights used here are the criterion weights obtained by the spherical fuzzy DEMATEL method. The weighted spherical fuzzy decision matrix is illustrated in Table 12.

Table 12: The Weighted Spherical Fuzzy Decision Matrix

	CR1			CR2			CR3			CR4		
A1	.592	.549	.095	.601	.537	.096	.479	.664	.151	.303	.821	.234
A2	.483	.658	.152	.125	.930	.129	.519	.626	.133	.444	.707	.142
A3	.401	.731	.203	.408	.723	.206	.397	.736	.202	.367	.772	.188
A4	.201	.885	.223	.273	.829	.310	.199	.887	.221	.245	.861	.280
A5	.103	.944	.104	.273	.829	.310	.479	.664	.151	.094	.953	.095
A6	.400	.750	.184	.303	.810	.249	.208	.878	.224	.094	.953	.095
A7	.401	.731	.203	.438	.697	.190	.376	.754	.219	.395	.749	.173

The sum of the criterion values of each alternative is calculated. Totals are displayed in Table 13.

Table 13: Sum Values of Alternatives

	$\tilde{S}$		
A1	.842	.161	.182
A2	.747	.271	.203
A3	.700	.300	.300
A4	.446	.561	.457
A5	.548	.495	.321
A6	.526	.508	.341
A7	.713	.288	.291

Spherical fuzzy sum values are defuzzied. These results are then sorted from largest to smallest. The S values of the alternatives are shown in Table 14.

Table 14: S Values

	S
A1	2.259
A2	1.662
A3	1.210
A4	0.178
A5	0.570
A6	0.477
A7	1.288

The ranking of strategy alternatives for energy independence according to S values is visualized in Figure 2.

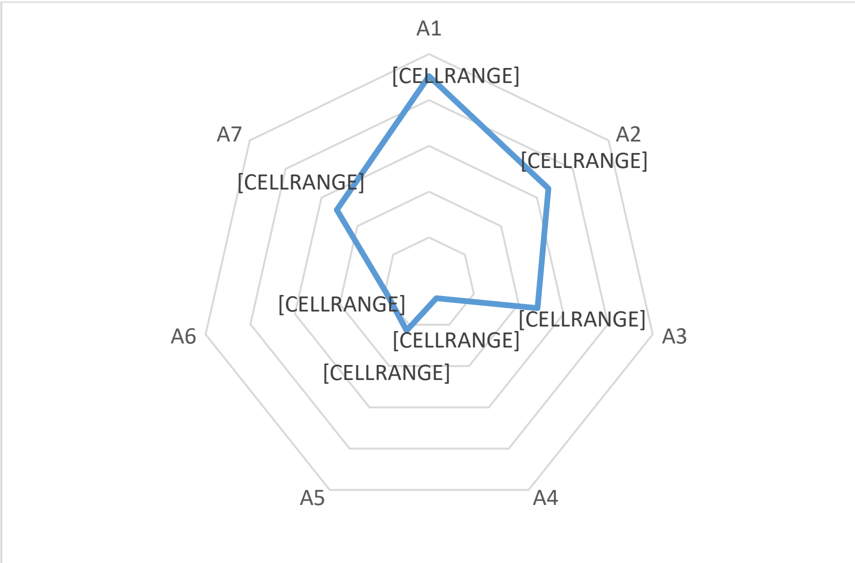

Figure 2: Ranking of Alternatives

As can be seen in Table 14 and Figure 2, nuclear and solar energy are the most critical investment alternatives for energy independence.

4. CONCLUSION

Critical strategies are defined in this study to provide energy independence. A new fuzzy decision-making model is created for this situation. Firstly, selected criteria are weighted with spherical fuzzy DEMATEL. Next, seven different investment alternatives are identified by using the details of the literature review results. These alternatives are ranked by spherical fuzzy SAW. Technological improvement is found as the most important criterion in energy independence. In addition to them, the ranking results indicate that nuclear and solar energy are the most critical investment alternatives for energy independence. The main contribution of this study is that effective strategies can be presented to obtain energy independence. With the help of this issue, the countries can focus on the most appropriate issues without having budget deficit. Moreover, considering DEMATEL methodology to weight the criteria provides some benefits. Owing to this issue, the causal relationship among the determinants can be identified.
Taking into account the results of this analysis, it is possible to offer some policy recommendations for countries to achieve energy independence. First, countries should focus on

their nuclear energy projects. Thanks to this type of energy, countries will be able to produce high amounts of electricity. Thanks to this situation, countries will not have to import electricity from other countries. However, there are some hesitations regarding nuclear energy projects. In the first stage, the explosion risk of these reactors and the resulting radioactive waste increase anxiety. Therefore, these safety problems need to be resolved to develop nuclear energy projects. To achieve this goal, two different issues are underlined in the literature. Firstly, thorium can be used instead of uranium in nuclear reactors. This allows minimizing both the risk of explosion and the waste problem. Secondly, it is possible to reduce the problem of high initial costs by using small-scale nuclear reactors. For both recommendations to be realized, countries need to increase their research activities.

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