Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 4, August 2024, pp. 2213~2220
ISSN: 2302-9285, DOI: 10.11591/eei.v13i4.7037

A fuzzy analytic hierarchy process model to enhance energy security: the case of Morocco

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Article Info

Article history:

Received Jun 20, 2023
Revised Nov 8, 2023
Accepted Dec 13, 2023

Keywords:

Energy policy
Energy security
Fuzzy analytic hierarchy process
Morocco
Strategic measure

ABSTRACT

Energy security has become increasingly important because of its impact on all sectors of the economy, and even more because of the scarcity of primary energy resources and price fluctuations caused by geopolitical tensions. This has prompted all countries to assess their energy situation and take strategic measures to mitigate energy risks. Accordingly, the aim of this study is to identify the dimensions of energy security with the greatest impact on Morocco's energy security, as well as the priority strategic measures for mitigating energy risk. To this end, we consider the fuzzy analytic hierarchy process (F-AHP) method, which is a multiple criteria decision analysis method, which has been used to obtain results based on a structured evaluation process. The obtained results, following the considered comparison matrix, underscore that availability and resilience dimensions have the greatest impact on the Moroccan energy security, with respective weights of 48% and 28%. Besides, mitigating energy risk in Morocco primarily involves the development of renewable energies compared with seven other proposed measures, along with their degree of priority.

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1. INTRODUCTION

Ensuring a continuous supply of energy has been and will continue to be the main objective of governments given its direct impact on all economic, industrial and social activities. The proper operation of hospitals, banks, administrations and factories is directly depending on the availability of continuous and reliable energy supply [1]. The concept of energy security has always been a focal point of governments [2]. After the Covid-19 pandemic, energy security has become more important because of the repeated closure of borders, the need of countries to be self-sufficient in energy resources and the instability of international prices. In this regard, it is important to note that the race of countries to secure supplies of primary energy resources following the revitalization of economies after the containment imposed by the health situation of Covid-19, has caused an unprecedented surge in energy prices. Even worse, energy prices have reached an all-time price records climbing from record to record. This period, which was considered as an "Energy Crisis", didn’t remain without impact on the finances of countries with high energy dependency, affecting the cost of most industrial products, particularly in energy-intensive industries, and impacting the overall energy security of some countries.

For this purpose, it's essential to delineate strategies for mitigating diverse energy risks and prioritize actions accordingly. To accomplish this, the initial step involves delineating the dimensions of energy security and quantifying their significance. However, since the weight of each dimension varies from one country to another based on factors like internal energy resources, geopolitical positioning, logistical connections, and energy requirements, in our study, we will focus on the case of Morocco to determine the weight of each dimension of energy security and provide policy-makers with energy policies in order of importance, taking into account Morocco's energy and geopolitical situation.

Regarding energy security dimensions, many studies have been conducted in order to define this concept and to determine its various dimensions [3], others to determine the single and composed indicators used to measure and assess energy security [4], [5]. Once the evaluation is conducted, the objective is to define the energy policy to be adopted. As an example of those energy policies, we can mention the strengthening of energy efficiency, energy storage development, diversification of supply and suppliers [6]. Nevertheless, due to numerous technical and financial limitations, establishing an energy policy necessitates ranking energy security dimensions by order of significance. In this context, several studies have been carried out, considering a range of dimensions [7], [8]. In the case of Morocco, Moore [9] has evaluated the energy security of the country based on four dimensions, which are availability, reliability, affordability, sustainable development and human security. The analysis has been conducted based on interviews with stakeholders and policy makers in the country; the study has been concluded by proposing three policies for improving energy security of Morocco without any prioritization analysis. Choukri *et al.* [10] have presented an overview of the Moroccan energy transition and development of renewables energies; by contrary Kouskso *et al.* [11] have conducted a study about Moroccan strategy for energy security and have concluded that wind energy is the most appropriate power generation alternative in Morocco at the current level. In summary, there has been no assessment or prioritization in terms of importance for either the dimensions of energy security or energy policy within the context of Morocco.

To provide an answer to the problematic, we will use fuzzy analytic hierarchy process (F-AHP) method in order to determine the relative weight or the importance of five dimensions of the energy security of Morocco, which are, availability, affordability, efficiency, sustainability, and resilience. Based on the results of this classification, we will suggest and prioritize the main energy policies that have to be adopted by political decision-maker. AHP is employed due to its ability to efficiently organize and structure the problem, establish relative weights, and select the optimal alternative using the pairwise comparison which can be applied to both quantitative and qualitative criteria [12], while the fuzzy theory has been utilized in this study in order to take into consideration the imprecisions in the judgments of experts during pairwise comparisons.

In this context, we establish in section two a clear understanding of the concept of energy security and its associated dimensions. In section three, we discuss the energy security landscape in Morocco, defining the dimensions under examination as well as the strategic measures for analysis. Section four introduce the F-AHP method, which will be used to assess the weight of each dimension and prioritize the strategic energy policies. Section five is dedicated to presenting and discussing the findings.

2. CONCEPT OF ENERGY SECURITY

The problem of energy security has never stopped to grow in importance because of the ever-increasing international energy demand, faced with a limited supply from a limited number of countries, some of which are politically unstable [13]. Besides, energy security has always been defined as the continuous availability of energy at affordable prices [14]. Also, it has been defined as equitably providing available, affordable, efficient, environmentally neutral, proactively governed, and socially acceptable energy services to end-users [15]. From an environmental side, energy security or, as Narula calls it, “sustainable energy security (SES)”, can be defined as provisioning of uninterrupted energy services in an affordable, equitable, efficient and environmentally benign manner [16]. Narula has confirmed also the importance of treating the concept of energy supply security from the demand side, because traditionally it has been considered that all energy demand can be met by increasing the supply, which means that solving the problem of energy security is limited in securing the supply source. Also, energy security has been defined as the ability of a country to protect itself from, or quickly recover from, sudden or prolonged shocks to the country's energy supply or infrastructure. In this definition, the resilience dimension of the energy security has been considered. To summarise, we can conclude that there is no single definition, but various definitions depending on the considered dimensions. At this regard, the concept of energy security is very wide, it can be treated from various dimensions and can be evaluated based on various indicators composing each dimension.

The concept of the four as has determined four dimensions for energy security which are: availability, affordability, accessibility, and acceptability. Availability indicates the existence and sufficiency of fossil fuels and other indigenous sources of energy to meet the region’s needs [17]. Many studies have confirmed the importance of this dimension in the energy security [18], [19]. Pavlovic and Ivezic [15] have emphasized in their study on the availability dimension and have defined five components composing this dimension which are security of supply (SOS), self-sufficiency, diversification, renewable energy sources and technological maturity. Affordability is related to the possibility to access to energy resources at reasonable prices. Accessibility refers to the possibility to reach the energy resources and acceptability focuses to the social and environmental acceptance of the energy sources. An other review study about energy security has identified seven dimensions which are energy availability, infrastructure, energy prices, societal effects, environment, governance and energy efficiency [20]. Infrastructure dimension includes storage facilities, pipelines, powerplants, ports, and refineries.

Energy security is therefore a multidimensional concept whose definitions differ according to the dimension from which it is analysed. In the present study, the energy security dimensions that will be considered are: availability, affordability, efficiency, sustainability, and resilience.

3. PROBLEM SETTING OF ENERGY SECURITY IN MOROCCO

3.1. Overview of energy security of Morocco

Morocco, a country heavily dependent on energy imports, is more than ever concerned with securing its primary energy imports and improving its energy security in general, especially in an international context where geopolitical tensions are constantly increasing. It is one of the African countries with limited energy resources, its economy has always been weakened by its energy dependency which was about 96% in 2012. This dependency has decreased in the last years thanks to the development of renewable energies.

The demand for electricity has registered a steady growing thanks to the economic development and the improvement of citizens living standards. Indeed, rural electrification has reached 99.64% in 2021, while electricity demand has passed from 14.11 TWH in 2000 to 34.56 TWh in 2019. The average annual increase in electricity consumption between 1990 and 2019 is around 4.84% with peaks of around 7.97% and 7.75% recorded simultaneously in 2011 and 2012 [21].

Furthermore, Morocco has been one of the most impacted countries in Africa from Covid-19, since the electricity mix in Morocco is based on about 60% of coal and natural gas which prices have been soared dramatically. For this reason, even if Morocco has already established an energy strategy based basically on renewables development and increasing demand-side energy efficiency [22], it is imperative to determine the priorities in term of energy security dimensions and strategic measures in order to protect the country against the impact of geopolitical movements, to limit energy dependence and to improve the resilience of the Moroccan electrical system against shocks.

3.2. Strategic measures considered for energy security evaluation

The strategic measures (SM) proposed to improve the energy situation of Morocco are as following: i) setting up national strategic reserves of primary energy sources (coal, fuel oil and natural gas) (SM1); ii) diversification of energy sources and suppliers (SM2); iii) developing renewables energies (solar and wind) (SM3); iv) developing energy storage systems (SM4); v) implementation of an intelligent billing system (SM5); vi) communication and marketing for promoting energy saving among citizens (SM6); vii) introduction of nuclear energy in the country's energy mix (SM7); viii) fiscal measures for modernization and promoting energy-saving technologies in all sectors of the Moroccan economy (SM8); and ix) the problematic can be schematized according to the Figure 1. We will first determine the weight of each dimension; then, we will prioritize the importance of the eight measures considered for improving energy security in Morocco.

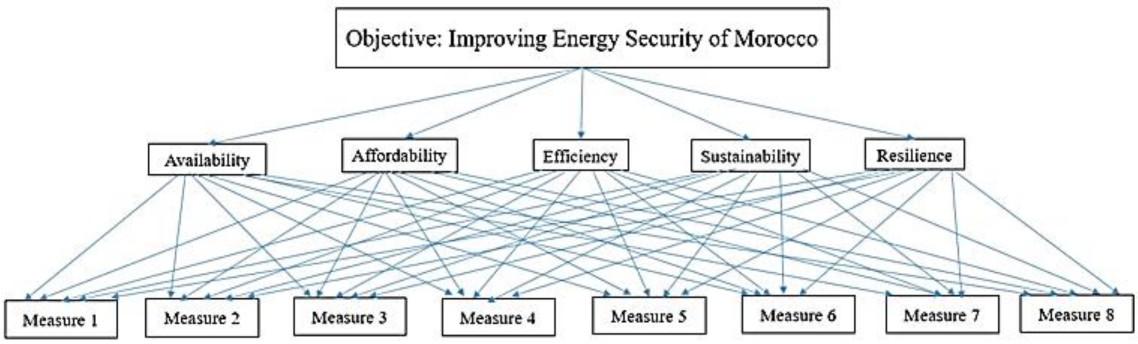

Figure 1. Dimensions for energy security in Morocco

4. PROPOSED METHOD

Several multi-criteria decision making methods are used to select an alternative taking into consideration several criteria and sub-criteria, namely: TOPSIS, AHP which is based on the experts opinions, ELECTRE, PROMETHEE, and analytic network process (ANP). But we have preferred AHP which is a decision-making tool, developed by Satty [23], and considered as the most widely used in various multi-criteria decision-making problems [24]. It consists on making comparisons between each two alternatives based on a given criterion. As the comparisons are subjective and the judgments can be vague and imprecise, then the AHP method has been completed by the fuzzy theory giving rise to the "F-AHP" method. The expression of the judgement uncertainties is done thanks to membership functions which can be triangular or trapezoidal. In our case we will use the triangular membership function whose mathematical representation is given in Figure 2.

$$\mu_A(x) = \begin{cases} 0 & \text{if} \quad x \leq a \\ \frac{x-a}{b-a} & \text{if} \quad a \leq x \leq b \\ \frac{c-x}{c-b} & \text{if} \quad b \leq x \leq c \\ 0 & \text{if} \quad x \geq c \end{cases}$$

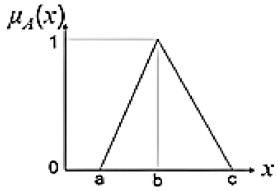

Figure 2. Triangular membership function in fuzzy logic

The steps to follow for the determination of the weight of each dimension are given as follows:
Step 1: determination of the dimensions of energy security to be weighted and the strategic measures to be prioritized.
Step 2: pairwise comparison and setting up of the corresponding matrix.

A pairwise comparison must be made between each two dimensions based on the linguistic scale giving in Table 1. The pairwise comparison between each two criterions will be represented in the following matrix, where $\tilde{d}_{ij}^k$ indicates the k^{th} decision maker's preference of i^{th} criterion over j^{th} criterion, via fuzzy triangular numbers.

$$\tilde{A}^k = \begin{bmatrix} \tilde{d}_{11}^k & \tilde{d}_{12}^k & \cdots & \tilde{d}_{1n}^k \\ \tilde{d}_{21}^k & \cdots & \cdots & \tilde{d}_{2n}^k \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{d}_{n1}^k & \tilde{d}_{n1}^k & \cdots & \tilde{d}_{nn}^k \end{bmatrix} \quad (1)$$

Table 1. The linguistic terms and corresponding fuzzy numbers for pairwise comparison

Linguistic scale	Abbreviation	Fuzzy scale
Equal importance	EI	(1,1,1)
Moderate importance	MI	(2,3,4)
Strong Importance	SI	(4,5,6)
Very strong importance	VSI	(6,7,8)
Extreme importance	EXI	(9,9,9)
Intermediate values	Will be designed with both abbreviations separated by a hyphen (example: EI-MI is the intermediate value of EI and MI)	(1,2,3) (3,4,5) (5,6,7) (7,8,9)
Reciprocal	RMI, RSI, RVSI, REXI	(1/4,1/3,1/2) and (1/6,1/6,1/4)

In case there are several decision makers, the average of $\tilde{d}_{ij}^k$ will be taken into consideration.
Step 3: calculation of dimension weights according to the following formulas:
a. Calculation of geometric mean of fuzzy comparison values of each dimension according to (2):

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij}\right)^{1/n}, \ \ i = 1, 2, \ldots, n \quad (2)$$

where $\tilde{r}_i$ is triangular values.
b. The fuzzy weight of criterion i is calculated (3):

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \quad (3)$$

Step 4: de-fuzzification and normalization of the fuzzy weights to get the weight of each dimension in the Moroccan energy security.

The weight M_i of the dimension *i* is the arithmetic mean of the three elements composing the fuzzy weight.

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \tag{4}$$

The normalized weight is calculated according to (5):

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{5}$$

Step 5: after determining the weight of each of the five selected dimensions of energy security, we will calculate the scores of the eight proposed strategic measures.
The calculation of the score will go through two steps:

a. Repeating steps 2 to 4 to calculate the weight of each action for the improvement of a given dimension *i* of energy security, which means that the calculation will be repeated five times.
b. The score or the weighted index for each strategic measure will be determined according to (6):

$$(P_i) = \sum_{j=1}^{5} w_j\, P_{ij} \quad i = 1,2,3,,\ldots,8 \tag{6}$$

where P_i is the weighted score of strategic measure *i*, w_j is the weight of dimension *j*, and P_{ij} is the weight of the strategic measure *i* with respect to the dimension *j*.

5. RESULTS AND DISCUSSION

In this section, to study and validate the proposed approach, we consider the case of Morocco with five dimensions and eight measures presented in section 3. Pairwise comparisons of the five dimensions results using linguistic terms and fuzzy numbers are giving respectively in the Tables 2 and 3. The Table 4 presents the fuzzy geometric mean, the weight and normalized weight according to abovementioned equations.

Table 2. Comparison matrix for evaluation of the five dimensions using linguistic terms

	Availability	Affordability	Efficiency	Sustainability	Resilience
Availability	EI	SI	SI-VSI	SI-VSI	MI
Affordability	RSI	EI	MI	SI	RMI-RSI
Efficiency	RSI-SVSI	RMI	EI	MI	RMI-RSI
Sustainability	RVSI-REXI	RSI	RMI	EI	RSI-RVSI
Resilience	RMI	MI-SI	MI-SI	SI-VSI	EI

Table 3. Comparison matrix for evaluation of the five dimensions using fuzzy numbers

	Availability	Affordability	Efficiency	Sustainability	Resilience
Availability	(1,1,1)	(4,5,6)	(5,6,7)	(5,6,7)	(2,3,4)
Affordability	(1/6,1/5,1/4)	(1,1,1)	(2,3,4)	(4,5,6)	(1/5,1/4,1/3)
Efficiency	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(1/5,1/4,1/3)
Sustainability	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/7,1/6,1/5)
Resilience	(1/4,1/3,1/2)	(3,4,5)	(3,4,5)	(5,6,7)	(1,1,1)

Table 4. Results of fuzzy geometric mean, the weight, and normalized weight

	Fuzzy generation mean	Fuzzy weight	Weight	Normalized weight
Availability	(2.89,3.52,4.11)	(0.33,0.48,0.69)	0.50	0.48
Affordability	(0.77,0.94,1.15)	(0.09,0.13,0.19)	0.14	0.13
Efficiency	(0.43,0.53,0.67)	(0.05,0.07,0.11)	0.08	0.07
Sustainability	(0.24,0.28,0.35)	(0.03,0.04,0.06)	0.04	0.04
Resilience	(1.62,2.09,2.45)	(0.19,0.27,0.41)	0.29	0.28

The results presented in Table 4 indicate that availability is the most significant factor contributing to energy security in Morocco, accounting for 48% of the total weight. Resilience follows as the second most important dimension representing a percentage of 28%. In the third position, we find affordability, with a weight of 13%. Efficiency and sustainability occupy the fourth and fifth positions with weights of 7% and 4%, respectively. The significance of availability as the primary dimension of energy security has been reaffirmed in multiple studies. Bašová [25] has emphasized that "diversification will remain the fundamental starting principle of energy security". Ren and Sovacool [18], have further confirmed that availability and affordability are the two most influential dimensions for energy security; however, their study did not encompass the resilience dimension.

Certainly, the recent energy crisis stemming from international geopolitic tensions has underscored that the primary focus and challenge for all countries was to secure the supply of essential energy resources, including gas, coal, and petroleum. The risk of power shortages in countries heavily reliant on energy was elevated to unprecedented levels, primarily due to the scarcity of raw materials in general and, specifically, primary energy resources. For Morocco, it is essential to highlight that natural gas and coal together account for over 60% of the electricity generation mix knowing that coal and gas prices surged dramatically in the last years. In order to establish an energy strategy that mitigates risks and ensures the country's energy supply at cost-effective rates, we will assess the impact of eight strategic measures, outlined in section three, on each dimension of the energy security; this assessment will involve assigning a weight to each measure with respect to each dimension.

In Table 5, we present the considered pairwise comparisons for strategic measures as regard to availability dimension. The results show that the development of renewable energies, including wind and solar power, has the greatest impact on the availability dimension, with a weighting of 39%. Indeed, increasing the share of renewable energies in Morocco's energy mix will limit the country's dependence on primary energy imports. However, the problem of intermittency constitutes the main obstacle to this measure, that is why the fourth measure which is the development of energy storage systems would enable the easy introduction of renewable energies into the energy mix; this strategic measure takes the third place with a weighting of 12%. The development of nuclear power comes second with a weighting of 23%; however, the main constraints to its development being the nuclear risk and the enormous initial investment cost.

Table 5. Comparison matrix of the impact of strategic measures on availability

Availability	SM1	SM2	SM3	SM4	SM5	SM6	SM7	SM8	Weight (%)
SM1	EI	RMI	RVSI	RMI	REI-RMI	MI-SI	RSI-RVSI	SI	5
SM2	MI	EI	RSI-RVSI	REI-RMI	MI-SI	SI-VSI	RMI-RSI	SI-VSI	11
SM3	VSI	SI-VSI	EI	SI	VSI	VSI-EXI	MI-SI	VSI-EXI	39
SM4	MI	EI-MI	RSI	EI	MI	MI-SI	RMI	MI-SI	12
SM5	EI-MI	RMI-RSI	RVSI	RMI	EI	MI	RSI-RVSI	MI	5
SM6	RMI-RSI	RSI-RVSI	RVSI-REXI	RMI-RSI	RMI	EI	RVSI	EI	3
SM7	SI-VSI	MI-SI	RMI-RSI	MI	SI-VSI	VSI	EI	VSI	23
SM8	RSI	RSI-RVSI	RVSI-REXI	RMI-RSI	RMI	EI	RVSI	EI	2

In the same way, we proposed, according to our expertise, the pairwise comparisons for strategic measures as regard to the other four dimensions. The Table 6 summarizes the obtained results, namely, the weights of each strategic measure as regard to the five considered. The results show that improving energy resilience in Morocco mainly involves setting up national strategic reserves of primary energy sources (coal, fuel oil, and natural gas). The development of renewable energies is the main measure that can improve sustainability and affordability due to their low production costs and environmental impact. Implementation of an intelligent billing system to encourage consumption during off-peak hours would smooth the load curve, facilitate the introduction of renewable energies and avoid the need for more expensive power generation during peak consumption periods. The development of nuclear energy has a major impact on the affordability dimension, thanks to the low cost of nuclear power generation. This strategic measure also permits the improvement of resilience and sustainability dimensions.

Table 6. Weights of strategic measure as regard to each energy risk dimension

	Availability (%)	Affordability (%)	Efficiency (%)	Sustainability (%)	Resilience (%)
SM1	5	2	2	2	37
SM2	11	3	3	2	10
SM3	39	30	10	35	16
SM4	12	4	6	5	6
SM5	5	17	33	10	4
SM6	3	8	15	6	2
SM7	23	31	7	18	23
SM8	2	6	25	22	2

In addition, using (6), we compute the scores for each strategic measure, which are graphically depicted in Figure 3. The result shows that the development of renewable energies is the most important strategic measure for enhancing Morocco's energy security. This conclusion aligns seamlessly with the results of several previous studies [26], [27]. Nuclear energy is another strategic measure worth considering due to its substantial and dependable energy output, as well as its ability to generate carbon-free electricity. However, its development necessitates substantial upfront investments, and the management of nuclear waste presents challenges. The establishment of strategic reserves of primary energy resources as coal, gas and fuel oil has an important role for enhancing the resilience of energy system, particularly in periods of energy shortage. Additionally, intelligent billing and energy storage represent two measures that facilitate the integration of renewable energy sources into the electrical grid. Energy storage enables the consumption of electricity generated from renewables during peak periods, while the intelligent billing objective is to smooth the electricity consumption pattern, avoiding consequently the use of fossil fuels during peak periods when the renewable production could be lower. Although energy saving measures are very important, but it is always more interesting to implement incentives that encourage consumers to rationalize their consumption as fiscal penalties for energy-intensive devices.

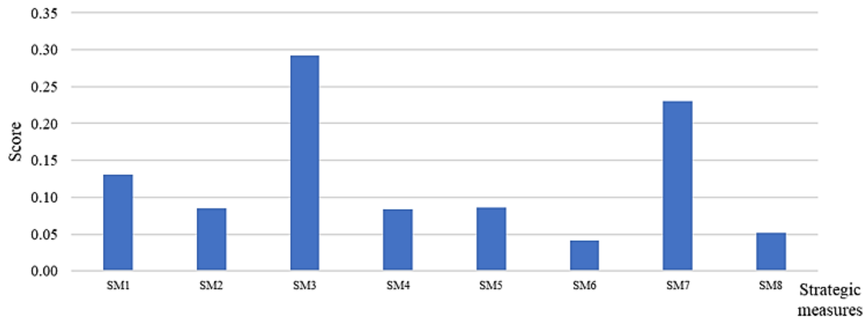

Figure 3. Scores of each strategic measure for enhancing energy security of Morocco

6. CONCLUSION

The application of F-AHP in this study has successfully accomplished two main objectives. First, it allowed us to compute the weight of each dimension contributing to Morocco's energy security. This analysis revealed that availability, resilience, and affordability hold the utmost significance in shaping any energy strategy for Morocco. Availability, with a weight of 48%, emerges as the top priority, underscoring the imperative need to enhance energy independence in the country. Secondly, we have provided Moroccan policymakers with a valuable tool for assessing the influence of each strategic measure on every dimension of energy security and how to establish a prioritized order for these measures. Among the eight measures proposed in this study, the development of renewable energy has demonstrated the most substantial impact across all dimensions, making it a vital mitigating factor for energy security risks in Morocco. These findings can be used by policymakers to adapt existing strategies and establish a dedicated energy index for Morocco. This index will facilitate the ongoing monitoring of the nation's energy landscape.

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