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Assessment of energy supply security using an analytic hierarchy process based approach

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ABSTRACT

In this paper, we are interested in analyzing the energy supply security using one or several indicators to measure the extent of the energy security for different countries. Given that each parameter can't give a clear idea about the energy supply risks, a composite indicator must be developped to summarize the information, to benchmark the countries and to monitor the efforts made to improve the security of supply. At this regard, based on analytic hierarchy process (AHP) method, we determine first the weight of a three considred parameters which reflect the supply situation in a general way. Then, we proposed a new linear composite indicator that mesures energy supply security taking into consideration the above-mentioned parameters. Afterwards, in order to verify the representativeness of this index, we calculate the new indicator for five energy supply situations and we test its sensitivity to each component.

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1. INTRODUCTION

Energy is considered as a fundamental pillar not only for the economic development of countries, but also for their social and political stability, security and sovereignty [1]. It is also a fundamental ingredient for all human activities. If the energy management from an economic aspect depends mainly from the purchasing and logistics costs; from a security perspective, it depends from several and multiple factors, namely, the availability of national and international energy resources, the availability of logistics and infrastructures including ports, gazoducs and storage facilities, geopolitical problems, the rate of consumption growth, and price volatility. All those parameters push governments to establish energy strategies to secure energy supplies.

Energy security is one of the three pillars of any energy policy next to energy efficiency and sustainability [2]. It is generally defined as "the sufficient availability of energy sources at affordable prices", but this definition remains vague due to the non-classification of the availability and variety of resources [3], [4]. Besides, following the oil crisis of the $1970s$ and $1979s$, the concept of energy security has become increasingly important because of its impact on all sectors. Then, ensuring energy security has evolved from the simple principle of ensuring a stable supply of oil at low prices to a more complicated concept taking into consideration several dimensions [5], [6].

The study of the energy security supply problem is complex. It requires its quantification by setting multiple parameters representing different dimensions which will allow the comparison of energy security situation between different countries. Given that, energy security supply can't be analysed by one parmeter, it can be seen as multi-criteria decision making problem. Several methods have been proposed giving rise to new composite indicators depending on the objective of the study [7]-[9]. However, the greater the number of parameters constituting an index, the less sensitive the index becomes to changes in the values of some parameters [10], [11].

The analytic hierarchy process (AHP) is one of various methods of multi criteria decision making. This method of weight determination is based on both experience and physical data, which means that quantitative and qualitative aspects are considered [12]-[16]. The AHP method is based on pair-wise comparison and has been criticized by various authors. One of the disadvantages cited are the changes in the criteria used for comparison over time and space; also, "the inconsistency issue arises and increases exponentially as the number of the criteria and alternatives grows" [17]. However, in the case of energy supply risk, we will consider only three parameters, we will rely on the opinions of experts in the field of energy in order to make the pair-wise comparison between them.

The aim of this paper is to analyse the energy supply security based on three parameters representing the availability dimension which is a very important issue in each energy policy. The three parameters are: energy mix concentration index (EMCI), energy import dependency index (EIDI) and energy origin concentration index (EOCI). To summarise the information containing in each parameter and in order to give a clear idea about the energy supply risks, we propose an AHP-based approach to develop a new linear index which take into consideration the three studied indices. The AHP method is used to determine the weight of each considered parameter, then, a combined linear formulation gives rise to a new index.

The remainder of this paper is organized as follows: section 2 is devoted to present the concept of the energy supply security and the considred indices. In section 3, we present the proposed AHP-based approach to analyse the energy supply securty of countries, in addition to a new composite index. Section 4 presents some results and discussion based on different data following five considered situations.

2. PROBLEM SETTING OF ENERGY SUPPLY SECURITY

Energy security is a broad concept that can be treated from several angles. The security of energy supply is a component of the energy security which is a more complete concept including several dimensions exceeding the supply part and including social, environmental, economic and geopolitical axes. Depending on the objective, researchers might use one or several of these dimensions to measure the extent of the energy security for different countries. The use of several indicators helps assessing a multi-dimensional reality, but a composite indicator is an added value which allowed summarizing the information, benchmarking the countries and monitoring the efforts made to improve the security of supply and the time trends. Several simples or composite parameters have been developed for security of supply in the recent years, as example, net-import dependence, diversity of suppliers, stock level, volatility of domestic production, political stability of suppliers, and volatility of hydropower production [18]-[20]. To develop a monitoring index for energy supply security, we have chosen three parameters that reflect the supply situation in a general way regardless of the type of energy or supply specifications or logistics. This index would not classify countries according to their energy supply risk, but rather would be used as a monitoring parameter to evaluate energy policies that would help the country to secure its energy supply.

2.1. Energy mix concentration index

Ensuring the diversity of energy sources used in power generation is one of the objectives of countries with limited internal energy resources, the EMCI is used to assess the degree of energy concentration [21]. It's formula is given by (1):

$$EMCI_t = \sum_{i}^{t} p_i^2 \tag{1}$$

where p_i is the percentage of the use of an energy source i. The value of the EMCI is between 0 and 1. The lower the value, the more diverse the energy mix. Diversity is also measured by the Shannon-Wiener index "H" [22]. It's formula is given as (2):

$$H = -\sum_{i} p_i ln p_i \tag{2}$$

where p_i represents the percentage of energy source i in the energy mix.

Unlike the EMCI index, the larger the H index, the more diverse the energy mix. The EMCI is less sensitive to diversity and gives more weight to the dominant energy sources. The Shannon-Wiener index is more sensitive to diversity even though the contribution of some energy sources to the energy mix is very small. As it is not the number of energy sources that is important, but rather the contribution of these sources to the energy mix.

2.2. Energy import dependency index

Energy import dependency for power generation can be defined as the ratio of power generation from imported primary energy sources to total power generation [23]. The formula for the EIDI is given as (3).

$$EIDI = \frac{\text{Electricity generation from imported energy sources}}{\text{Total electricity production}} \tag{3}$$

2.3. Energy origin concentration index

Diversification of suppliers or origins can be determined by considering the number of suppliers or origins that provide the primary energy, or the number of origins or countries from which deliveries are made, or both [24]. However, from a risk perspective, it is more appropriate to diversify origins than suppliers to mitigate the climatic and political risks associated with exporting countries. The measure of the diversification of origins can be done according to the following EOCI given by (4):

$$EOCI = \sum_j q_j^2 \tag{4}$$

where q_j is the percentage of each origin of imported energy used for the electricity production.

3. THE PROPOSED METHOD

In order to evaluate the energy supply situation for a given country in general, we propose to combine the aforementioned indices taking into consideration the importance or weight of each index. At this regard, we use the AHP-method to determine the weight of each parameter. Secondly, we normalize the parameters and define the new index. Finally, we analyze the representativity of the new index of the real situation of a given country. The different steps for the proposed approach is given as follows.

Step 1: define the problem: construct a linear composite index "$CompIndex$" from the considered indices $(Index_i)_{1\leq i\leq n}$ in the form:

$$CompIndex = \sum_{i=1}^{n} \omega_i \times Index_i \tag{5}$$

where, ω_i is the wheight of each $Index_i$.

Step 2: compute the pairwise comparison matrix for the considered indices in the form:

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix} \tag{6}$$

the matrix $A = (a_{ij})$, $i, j = 1, ..., n$ has a positive entries everywhere and satisfies the reciprocal property $a_{ji} = 1/a_{ij}$. The comparison is done between each two parameters following each subjective expert opinion which will be transformed to a quantitative data. Table 1. present the relative significance scale suggested by Saaty [25].

Step 3: normalization of the pairwise comparison matrix to get the normalized matrix A_N given by:

$$A_N = \begin{pmatrix} \frac{1}{\sum_{i=1}^{n} a_{i1}} & \frac{a_{12}}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{a_{1n}}{\sum_{i=1}^{n} a_{in}} \\ \frac{a_{21}}{\sum_{i=1}^{n} a_{i1}} & \frac{1}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{a_{11}}{\sum_{i=1}^{n} a_{i1}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{a_{n1}}{\sum_{i=1}^{n} a_{i1}} & \frac{a_{n2}}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{1}{\sum_{i=1}^{n} a_{in}} \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} & \cdots & N_{1n} \\ N_{21} & N_{22} & \cdots & N_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ N_{n1} & N_{n2} & \cdots & N_{nn} \end{pmatrix}$$

and calculate the weights ω_i for each $Index_i$ for $i = 1, ..., n$.

$$W = \begin{pmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{pmatrix} = \begin{pmatrix} \frac{N_{11}+N_{12}+\cdots+N_{1n}}{n} \\ \frac{N_{11}+N_{12}+\cdots+N_{2n}}{n} \\ \vdots \\ \frac{N_{n1}+N_{n2}+\cdots+N_{nn}}{n} \end{pmatrix}$$

Step 4: calculate the consistency ratio (CR) given by:

$$CR = \frac{CI}{RI} \tag{7}$$

where CI is the consistency index given by:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \tag{8}$$

RI is the consistency random determined in [25] and given in the Table 2, and λ_{max} the largest eigenvalue of the normalized comparison matrix given by:

$$\lambda_{max} = \frac{V_1 + V_2 + ... + V_n}{n} \tag{9}$$

with $V = (V_1, V_2, ..., V_n)$ the eigher vector.
Step 5: if $CR < 0.1$ result accepted, else return to step 2.
Step 6: determination of the new index using the formula given by (10).

$$CompIndex = \sum_{i=1}^{n} \omega_i \times Index_i \tag{10}$$

Remark: it should be noted that we have to normalize the composite indices calculated based on several parameters having diferente units and values. To this end, several methods can be used, the most known are min-max, standadization, distance to reference and z-score [26], [27].

Table 1. The relative significance scale

Scale	Numerical rating	Reciprocal
Extremely preferred	9	1/9
Very strong to extremely preferred	8	1/8
Very strong preferred	7	1/7
Strongly to very strongly preferred	6	1/6
Strongly preferred	5	1/5
Moderately to strongly preferred	4	1/4
Moderately preferred	3	1/3
Equally to moderately preferred	2	1/2
Equally preferred	1	1

Table 2. Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

4. RESULTS AND DISCUSSION

In this study, we consider three parameters: EMCI, EIDI, and EOCI. Using the proposed approach, we calculate a linear index called dependency and concentration of energy types and origins (DCETO). A comparison of DCETO index is carried out among five energy supply scenarios.

4.1. Weights detarmination

Based on the opinions of more than twenty experts in the field of energy, the obtained Pairwise comparison matrix is given in Table 3. We normalize the pairwise comparison matrix and we calculate the weights of each index. The detail of the calcul process of weights is given in Table 4.

Table 3. Pairwise comparison matrix for the three indices

	EMCI	EIDI	EOCI
EMCI	1	$1/5$	4
EIDI	5	1	7
EOCI	$1/4$	$1/7$	1
Sum	6.25	1.34	12

Table 4. Normalized pairwise comparison matrix and the corresponding weight for each index in %

	EMCI	EIDI	EOCI	Weight in %
EMCI	0.160	0.149	0.364	22.42
EIDI	0.800	0.745	0.545	69.67
EOCI	0.040	0.106	0.091	7.91
Sum	1	1	1	100

4.2. Analysis of consistency

The component of the eigher vector of the normalized matrix is as:

$$V_{EMCI} = \frac{(1 \times 0.2242) + (0,2 \times 0,6967) + (4 \times 0.0791)}{0.2242} = 3.0328 \tag{11}$$

$$V_{EIDI} = \frac{(5 \times 0.2242) + (1 \times 0,6967) + (7 \times 0.0791)}{0,6967} = 3,2901 \tag{12}$$

$$V_{EOCI} = \frac{(0.33 \times 0.2242) + (0.14 \times 0,6967) + (1 \times 0.0791)}{0.0791} = 2,9669 \tag{13}$$

then, the eigher value is given by:

$$\lambda_{max} = \frac{(3,0328 + 3,2901 + 2,9669)}{3} = 3,0966 \tag{14}$$

so, the consistency Index calculated with the (8) is equal to: $CI = \frac{3.0966-3}{2} = 0,0483$, and the consistency ratio given in (7) is equal to: $CR = \frac{0,0483}{0.58} = 0.0833 < 0.1$. The consistency ratio is lower that 10%, which means that the matrix is consistent.

4.2.1. Normalization

In our case, the three parameters have values between 0 and 1; also, for the three parameters, more the value is low more the energy security situation in better. As a result, no need for normalization for the composite index. As mentioned earlier, security of energy supply depends on the level of dependency on imports of the primary energy sources needed for electricity production, the concentration level of energy sources in the energy mix and the diversity of importations countries and their sovereign risk rating. The proposed index is the dependency and concentration of energy types and origins (DCETO) index given by (15).

$$DCETO_{Index} = 0,22 \times EMCI + 0,7 \times EIDI + 0,08 \times EOCI \tag{15}$$

The values of this index are between 0 and 1. The lower the value of this Index, the better the country's security of energy supply situation.

4.3. Sensitivity analysis

In order to determine the sensitivity of the DCETO index, we set two parameters constituting the DCETO index to a value of 0.5, and recorded the evolution of DCETO index as function of the third parameter. The results presented in Figure 1 show that the energy dependency indicator has more impact on the value of the DCETO index while the EOCI index has the least impact. Indeed, a variation of 40% in the values of EMCI index and EOCI index impacts simultaneously the DCETO index by 3% and 9%, the same variation in the EIDI index impacts DCETO index by 28%. The sensitivity analysis shows that improving the energy situation in terms of supply risk involves limiting mainly the dependence of power generation on imports of primary energy resources.

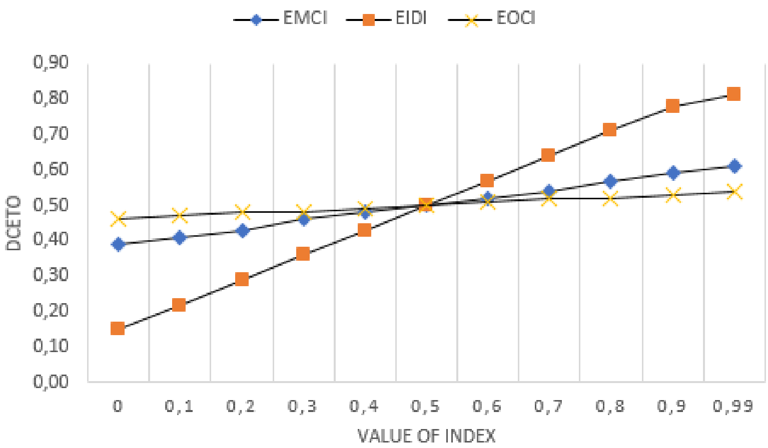

Figure 1. Sensitivity analysis of DCETO index according to EMCI, EIDI, and EOCI parameters

4.4. Comparison of the DCETO among five energy supply scenarios

In order to evaluate the representability of this index and how it reflects the real energy supply security of a country, we have calculated the DCETO Index for five diferents situations as shown in Table 5.

- Situation 1: a country with a high energy dependency of 78%, a varied energy mix with an average domination of one energy source and an average concentration of supply sources.
- Situation 2: a country with total energy independence but whose production is based on a single energy source (gas or coal for example).
- Situation 3: a country with a high energy dependency of up to 90%, the energy mix is dominated by a single source of energy that is mainly delivered from a single source.
- Situation 4: a country with a relatively low energy dependency of 30%, a very diverse energy mix and a wide variation of supply sources.
- Situation 5: a country with a high energy dependency of about 80%, a very varied energy mix and a high variety of supply sources.

The index recorded the lowest values for situation 2 and 4 with reciprocal values of 0.30 and 0.29. In situation 2, the supply risk is low because it is based solely on local production, even though the energy mix is dominated mainly by a single primary energy; the DCETO index value for situation 4 shows that a low energy dependence, of the order of 30%, can be compensated by a very wide diversification of supply sources and, above all, of the types of primary energy used for production. The DCETO index values for situations 1 and 5 show that in the case of high energy dependency, diversification of the energy mix and supply sources has only a limited impact on the index. Situation 3 illustrates the case of a country with a high energy dependency with an energy mix that is mainly based on a single primary energy supplied from a very limited number of countries, the value of the DCETO index is very high at around 0.92, referring to a situation that presents a very high supply risk, which can jeopardize the country's economy, and a high dependency on one or two countries that can limit even the political orientations.

Table 5. DCETO index in comparison with different parameters for five situations

Situations	Parameters	DCETO index
Situation 1	EMCI= 0.60, EIDI= 0.80, EOCI= 0.60	0.74
Situation 2	EMCI= 0.99, EIDI= 0, EOCI= 0.99	0.30
Situation 3	EMCI= 0.91, EIDI= 0.90, EOCI= 0.90	0.92
Situation 4	EMCI= 0.24, EIDI= 0.30, EOCI= 0.40	0.29
Situation 5	EMCI= 0.20, EIDI= 0.80, EOCI= 0.20	0.62

5. CONCLUSION

In this paper, we are interessted to the energy supply security which is a complex problem, knowning that it exists a large number of parameters from several dimensions to be considered to assess the energy situation. This parameters can allow to quantify the risk incurred for the energy supply. It has been shown that a single index will never be able to give a global idea about the energy situation from a security perspective. So, we proposed a new composite index based on three parameters, representing the availability dimension, based on AHP which is one of various methods of multi criteria decision making. The representability of this index and how it reflects the real energy supply security of a country is discussed for five diferent situations.

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