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A novel energy poverty evaluation: Study of the European Union countries

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ABSTRACT

Energy plays a pivotal role in economic growth. Besides, it is a requirement for the factories to be run, Industries to be developed, cities to have functioned, and populations to fulfill their needs and expectations. Thus, energy has a strategic position among nations and countries. Align with sustainability, nations want to have energy justice among various generations.

In this regard, this study developed a comprehensive framework based on a complete literature review, to evaluate energy poverty (EP) by addressing the energy demand, clean generation of the energy, its strategic position, and energy justice among the nations. As a consequence, the EP framework consists of three pillars. The first one is for society to address the demand, access, and affordability of energy. The second pillar is administration to ensure the accessibility to the sources of energy as well as aligning the energy market by their import policies. The third EP pillar is sustainability and refers to the emissions which result from the energy generations and level of renewable energy sources to satisfy the energy demand. By considering these three pillars, energy would be accessible, affordable, and sustained among various generations.

The comprehensive EP framework is applied in a case study with real data by using the European Union (EU) energy goal (7th goal) among the sustainable development indicators. The EP comprehensive framework is implemented to evaluate 27 EU countries based on the EU database in this case study by using the Indifference Threshold-based Attribute Ratio Analysis (ITARA) to weigh up the criteria set since this method is the recommended method in case of dealing with real data and assist the study to accurate and independent to the expert background and their attitude. Also, Measurement Alternatives and Ranking according to COmpromise Solution (MARCOS) methodology is used to evaluate the EU countries as the methodology uses both positive and negative ideal solutions to make sure the accuracy and convergence speed particularly when the problem is confronted by a long list of the 27 EU countries.

1. Introduction

According to the statistical review of the world energy published by British Petroleum (BP), the global primary energy consumption from various sources (i.e. fossil fuels, nuclear energy, and renewables) is 557.1 Exajoules in 2020 (BP 2021). Considering the global population in 2020, the energy use would be 71.5 Gigajoules per capita. However, energy use is remarkably diverse among the nations depending on their standard of living and their countries' development rates. For instance, annual energy consumption among EU countries is 125 while African countries only consume 13.9 Gigajoules per capita (BP 2021). Thus, establishing justice in access to resources is a vital issue. On the other hand, more developed countries seek to provide access to energy sources without any difficulty. In this regard, EU Energy Poverty Observatory (EPOV) primarily focused on consensual and expenditure indicators and investigated gaining the advantage of energy without confronting any significant budgetary difficulties [1]. By this definition, statistics in 2009 represent that between 50 and 125 million people in the EU countries are confronting poor energy access [2]. Energy Poverty (EP) is the associated concept in the context of having reliable and affordable access to clean energy for everyone and can be regarded from various perspectives.

Moreover, the world is dealing with one of the largest energy crises regarding the Russian-Ukraine war. According to the International Energy Agency [3], this crisis is serious owing to the fact that Russia is the largest gas exporter in the world. Also, as specified in this report, the

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largest release of the emergency oil reserves in the history of IEA since 1974 was granted in March and April 2022 by the EIA members to cover the energy shortage caused by this crisis. Besides, this crisis is even more severe in EU countries since 2019, Russia supplies 40% of EU natural gas, 25% of their oil, and 50% of their coal demand [4]. This Energy supply crisis put more emphasis on the importance of energy availability, energy security, and energy policy which are summed up in the EP concept.

Energy is a significant issue that is addressed by diverse countries around the globe. Regardless of the development rate of countries, energy is always the primary and momentous objective. Accordingly, the objective contains ensuring reliable access to various energy sources, having reasonable prices and being affordable, and producing clean and sustainable energies. Imposing any restriction on the mentioned objectives can compromise the objective and cause poverty in the current or future generations' energy supply. In this regard, 90.5% of the world's population in 2020 has access to electricity [5]. While, more than 80% of the global energy supply is originated from fossil fuels (Oil, Gas, Coal) [6]. Fossil fuels adversely affect the environment and are one of the main players in unsustainable development. In the meanwhile, governments are the strategic actors and have a pivotal role in demonstrating long-term policies, mid-term strategies, and short-term incentives. Energy problems are complicated because of the following reasons:

- **Multi-level:** Energy problems can be regarded from multiple levels from policy-making [7] to energy efficiency measures in a building [8] in the operating condition.
- **Multi-stakeholder:** Energy is the problem of various stakeholders for instance environmentalists, economists, industries, households, designers, and developers. For instance, a recent study considered various internal and external stakeholders, their interests, satisfaction, and influence in successful renewable energy projects [9].
- **Multi-disciplinary:** Various engineering disciplines such as electrical and mechanical engineers, architectures, and academic researchers. As a consequence, multi-disciplinary perspectives in the context of energy sector problems are investigated in a previous study [10]. Also, professional disciplines such as Construction, operation, fabrication, and transportation parties are involved in energy sector problems. A previous study focused on a comprehensive assessment of sustainability for a fossil fuel energy production industry and considered construction as well as pre and post-construction phases in their proposed framework [11].
- **Multi-criteria:** Energy evaluations engage with various criteria such as demand control, social and environmental factors, energy efficiency, and energy-economic. Various studies are focusing on multiple different criteria in the energy sector problems, for instance, a sustainability assessment of a petroleum refinery project as an important infrastructural energy generation field, considered sustainability pillars i.e., social, economic, and environmental aspects in its life-cycle assessment [12].
- **Multi-timeframe:** Energy problems raise along the time. Embodied energy in the cradle-to-gate phase, energy efficiency in the gate-to-gate section, and providing clean and sustainable energy production methods in the gate-to-grave phase are examples of the energy problems across the material life-cycle. For instance, three different hydrogen production technologies by using solar energy are investigated in a life-cycle assessment and combined with four environmental concerns to have a more comprehensive assessment [13].
- **Multi-front:** Regarding the importance of providing reliable energy in order to satisfy human needs. Researchers are carrying out studies on multiple fronts to ensure effective and efficient energy generation. The following fronts can be addressed in this context:
  - o **Sources:** studies cover various sources of energy [14] and seek to have renewable resources [15].
  - o **Energy footprints:** embodied energy and studying the inventories and databases on economic, environmental, and social footprints in the energy supply chain [16].
  - o **Access to energy:** some other studies are focusing on energy poverty and the secured access to reliable and affordable energy by the nations [17].

EP not only has inherent complexity of various perspectives which is reflected in its diverse definitions but it is also discussed in the context of energy problems which are complicated as mentioned before. This study proposes a novel definition of the EP by considering the mentioned complexities. Then, by using the EU energy database and mapping the EP concept onto the EU countries' perspectives, a case study is implemented and discussed in the EP among the EU 27 countries.

2. Literature review

When discussing energy problems and particularly when EP is being studied, one of the most important and fundamental issues is the source of energy supply. In this regard, a wide variety of studies especially in recent years are focusing on renewable sources of energy such as wind, solar, geothermal, bioenergy, hydropower, and ocean energies [18]. Solar energy in the meanwhile has more frequent utilization. For instance, diverse technologies are adopted to produce solar energy to align with sustainability and mitigate climate change [19]. One of the most important industries for solar energy is the building industry and rooftop technologies are highly used and optimized to provide buildings' energy demand [20]. Rooftop panels and photovoltaics in dense cities particularly are smart solutions [21]. Also, the wind is another renewable source of energy utilized in buildings. High-rise buildings in modern cities surprisingly can be a powerful source of energy and can operate as distributed wind turbines integrated by the buildings [22]. These wind energy generators are scrutinized to design properly and to be more optimized in more recent studies [23]. Other sources such as ground source heat pumps are also investigated in a review paper [24] which can be used to satisfy building energy demand. Buildings and households are the key players in energy supply and definitions of the EP. Hence, regarding the building's energy demand, the existing building frequency, and the growing rate of new building projects, developers need to have sustainable access to the building energy and utilities. A trend of studies as a consequence focused on the sustainability and resiliency of the buildings in an integrated and comprehensive view [25].

Away from the accelerating trend and growing number of publications on the renewable sources of energy supply especially for buildings and households, another trend focused on the limitations and restrictions of renewable sources of energy. Accordingly, some studies mentioned the renewable energies' higher Capital Expenditure (CapEx) [26], their land requirements [27], their dependencies on the weather condition [18], and their required storing mechanisms [28].

The renewable energies' limitations of technologies and restrictions on accessibility on one hand, and dependencies of the economics on the non-renewable sources of energy on the other hand make the energy supply even more complicated. These economic dependencies include the large share of fossil fuel in the energy supply and a considerable portion of professional job opportunities in the supply chain of non-renewable energies. Thus, another trend in the energy supply is to define a greener transition towards renewable energies. As a result, by considering the larger image and by taking various generations into the account, some studies propose using inter-generational strategies in renewable energy utilization and emphasizing the effective use of fossil fuels at the current stage [29]. Accordingly, having an effective fossil fuel industry align with sustainability in order to minimize the negative effects and enhance positive ones is under investigation in recent studies [30].

Apart from the sources of energy and arguing how to provide adequate energy supply, energy demand is an important subject in studying the EP concept. Recently researchers study on the inter-dependencies of energy efficiency and other sustainable development goals [31]. Also, inter-dependencies of the energy efficiency and EP are subjected to another study [32]. Another study in this regard focused on the relationship between energy efficiency policy and EP for building industry projects [33]. In order to have an efficient building and minimize the energy demand, there are diverse energy strategies utilized in buildings starting from the shell to the core. For instance, shading devices [34] and insulations [35] are highly influential to have an energy-efficient building and have low-cost strategies for decreasing building energy demand. The more moving toward the core from the shell, the higher the incremental cost.

2.1. Energy poverty definition

Some studies define EP as having any considerable inconvenience such as spending a large share of income to gain access to the basic energy demand by the households [36]. This concept of affordability is regarded as fuel poverty in another study on the demonstration of energy vulnerability in England [37]. In the literature, some scientists put more emphasis on the difference between affordability and availability of the energy required by households. Consequently, a researcher offers a strict definition of energy poverty and fuel poverty as lack of availability and affordability respectively [38]. EP has a rich literature and is investigated in both developing [39] and developed countries [40]. The dual approach of affordability and availability mainly originated from the development rate of the countries and depends on the nations' needs, expectations, and standard of living. As a result, EP in more recent studies has a more comprehensive definition and covers both availabilities of the physical infrastructure as well as the accessibility of various sources of energy [17].

Also, EP regarding its position and importance is considered from various other views. Some of the major perspectives are presented as follows:

- Health and social criteria: studies in this category mainly focused on self-assessed health and the relationship with the EP [41]. Also, the effect of EP on health conditions is investigated and their correlation is proved in Turkey [42].
- Location criteria: the effect of geographical location is demonstrated [43]. Accordingly, EP has a higher impact on the lower-income areas and is more influential in the Urban areas.
- Economic criteria: EP regarding the affordability pillar is inherently connected with the economy. However, some studies mainly focused on the ratio of energy cost and household income in Cyprus [44] and China [45].
- Political criteria: In this category, energy planning and policy-making are targeted. In this regard, a study scrutinized various projected energy scenarios to have a better energy strategy [46]. Also, another study in this regard focused on the growing rate of EP among the EU counties and questioned the existing energy policies [47].

Energy is used to satisfy social needs by developing the economy in the context of the environment and natural resources. Then, if a country has imposed any restrictions on the mentioned factors (i.e., development, society, and environment), EP would have occurred. By the abovementioned definition, EP contains three pillars as the following (refer to Table 1 for describing the development steps of the EP concept and Fig. 1 for the final framework):

- **Administration:** The development factor is representative of the government's policies and strategies to provide unrestricted and equal access to various sources of energy.
- **Society:** The society factor reflects the energy demand which has to be affordable, accessible, and available within their budget. Energy justice in satisfying the human energy demand is an important issue in this category.
- **Environment:** Energy can be produced by a variety of methods. From the perspective of energy resources, energy can be divided into two categories of renewable and non-renewable energies. This pillar of the EP definition refers to the sources of energy and trying to preserve finite non-renewable energy sources on one hand and preventing environmental degradation while generating the various types of energy on the other hand to ensure the sustainable generation of energy.

Table 1
EP definition process.

Energy Poverty => Developed Countries Fuel Poverty => Developing Countries Sustainability => Contribution of This Study	Society => Affordability Administration => Availability Environment => Renewables
The Novel Energy Poverty	**Combination**

3. Methodology

Regarding the mentioned complexities and inherent characteristics of the energy problems (e.g., multi-level, multi-stakeholder, and multi-criteria), Multiple Criteria Decision Making (MCDM) methodologies well coincide best with these types of problems. Due to this close correspondence between MCDM methodologies and multi-aspect energy problems, there are a wide variety of studies and publications on the application of MCDM in energy sector problems. In the first instance on the application of MCDMs in assessing renewable energy technologies, a recently published review paper acquires 271 journal papers only in the field of residential and household energy demands [48].

Besides, various enablers and features are developed in recent years. Thus, this study proposes MCDM tools to be used in this complicated decision environment and to cope with future uncertainties. EP evaluation based on the proposed integrated framework can be divided into two separate and independent problems as follows:

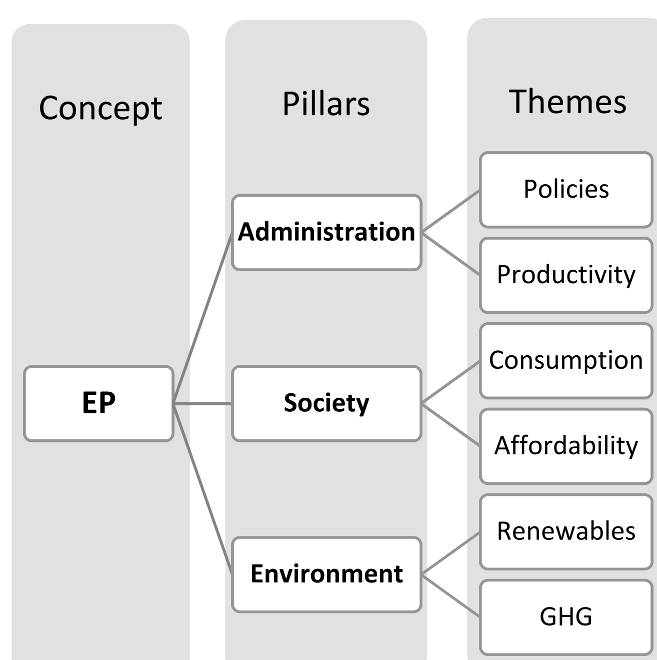

Fig. 1. The novel EP framework.

- **Criteria Assessment:** One of the highly significant problems in dealing with multi-criteria decisions is the decision-makers, their characteristics, background, and preferences particularly when they want to assess the criteria. It may arouse irrational prejudices and may question the accuracy of the study results. Fortunately, the ITARA methodology offers a solution to this serious dilemma of weighing the criteria set by using the decision-matrix and examining internal variations of the criteria vectors, and considering a minimum threshold to make sure only significant deviations take part in the criteria weighting process. This method is highly recommended when the study incorporates real data into the decision matrix [49].
- **Countries Evaluation:** The second problem is to evaluate MCDM alternatives which are EU countries in this study. MARCOS is among new MCDM methodologies which aim particularly at enhancing the efficiency and convergence speed of the older methods. Thus, the MARCOS methodology is comprised of negative and positive ideal solutions and seeks to maximize and minimize the alternatives from these extreme points simultaneously. On the other hand, since this study deals with multiple alternatives (i.e. 27 EU countries) this method is selected to be applied in this part of the problem [50].

3.1. ITARA methodology

ITARA at first applied to the material selection problems [51] then the methodology is used in other fields such as sustainability and the building industry [25].

This section seeks to provide some information to explain the ITARA methodology and other detailed calculation steps that can be followed in the mentioned applications. Thus, the calculation process can be summarized in the following 3 steps:

3.1.1. Preparation

ITARA like every other MCDM methodologies initiates with the decision matrix as follows.

$$\overline{X} = \begin{bmatrix} x_{11} & \cdots & x_{1,n} \\ \vdots & x_{ij} & \vdots \\ x_{m1} & \cdots & x_{m,n} \end{bmatrix}$$

while “m” alternatives and “n” criteria are in the matrix.

Also, every criterion needs to provide an indifference threshold based on the specific characteristic of the criterion. Thus, we have a single dimension vector of $IT_j, j = \{1, \ldots, \text{n}\}$.

Then, in order to have a unitless and comparable matrix, every matrix element as well as elements of the “IT” vector need to be normalized as follows:

$$\alpha_{ij} = \frac{x_{ij}}{\sum_i x_{ij}}$$

3.1.2. Calculating differences

In order to be able to calculate the differences, every criterion vector needs to be sorted and ordered. So, $\overline{\beta}$ is the sorted matrix which is sorted by its columns (i). $(\beta_{ij} \leq \beta_{i+1,j}, \forall i \epsilon \{1, \ldots m-1\})$. Then, the ordered matrix is $\overline{\gamma}$ which calculates the difference between elements of the sorted matrix as follows:

$$\gamma_{ij} = \beta_{i+1,j} - \beta_{ij}, \forall i \epsilon \{1, \ldots m-1\}$$

3.1.3. Final weighting

Considerable differences can be calculated by comparing the $\overline{\gamma}$ elements by the indifference threshold and to calculate the $\overline{\delta}$ matrix as follows:

$$\delta_{ij} = \begin{cases} \gamma_{ij} - NIT_j & For\ \gamma_{ij} > NIT_J \\ 0 & For\ \gamma_{ij} < NIT_J \end{cases}$$

Then, the root sum square is calculated ($\overline{v}$) as an aggregation method to measure the considerable distances and final weights ($\overline{w}$) at the end.

$$v_j = \sqrt{\sum_i \delta_{ij}^2} \Longrightarrow w_j = \frac{v_j}{\sum_j v_j}$$

3.2. Marcos methodology

Marcos is the other MCDM methodology applied to evaluate the alternatives. The methodology is also used in previous studies and applied to the energy industry projects as well [29]. This section seeks to briefly explain the methodology in a sequence of calculation steps and for more details refer to the previous application papers. MARCOS can be divided into the following three steps:

3.2.1. Preparation

The primary matrix includes decision matrix, ideal, and anti-idle solutions as the following:

$$\begin{bmatrix} X_{aa} \\ \overline{X} \\ X_a \end{bmatrix} = \begin{matrix} x_{aa1} & \ldots & x_{aan} \\ \end{matrix} \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & x_{ij} & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \begin{matrix} x_{ai1} & \ldots & x_{ain} \end{matrix}$$

Where ($\overline{X}$) is the primary decision matrix. (X_{aa}) and (X_a) are the anti-idle and idle solutions defining every criterion. Elements of the idle and anti-idle solutions are defined based on the negative or positive nature of the criterion and element of the criterion vector. For instance, the element of “x_{ai1}” is the maximum value among the elements of the vector ($\overline{X_{i1}}$) if the first criterion is a beneficial one.

Then, in order to have unitless elements the normalization ($\overline{N}$) process would be done based on the idle solution and the characteristic of the criteria as the following:

$$n_{ij} = \begin{cases} \frac{x_{ij}}{x_{ai}} \rightarrow \text{if Criterion}_j\ is\ Beneficial \\ \frac{x_{ai}}{x_{ij}} \rightarrow \text{if Criterion}_j\ is\ Cost \end{cases}$$

Afterward, the weighted matrix ($\overline{V}$) is calculated by multiplying the criteria weight by the normalized matrix ($v_{ij} = n_{ij} \times w_j$).

3.2.2. Utility degree

Utility degree matrix ($\overline{S}$) is calculated for every alternative by summarizing the weighted matrix elements $\left(S_i = \sum_j v_{ij}\right)$.

Then, Utility values are calculated based on the utility matrix elements in combination with idle and anti-idle solutions as follows:

$$\begin{cases} K_i^- = \frac{S_i}{S_{aai}} \\ K_i^+ = \frac{S_i}{S_{ai}} \end{cases}$$

3.2.3. Final weighting

Utility functions are calculated based on the utility elements as follows:

$$\begin{cases} f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \\ f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \end{cases}$$

MARCOS methodology proposes the final utility function in an aggregation function by combining previous utility elements and their function to provide the final utility function as the following:

$$f(K_i) = \frac{K_i^- + K_i^+}{1 + \frac{1-f(K_i^+)}{f(K_i^+)} + \frac{1-f(K_i^-)}{f(K_i^-)}}$$

Alternatives are weigh-up and ranked based on the final utility function for alternatives.

4. Case study

In order to apply this study to a real-world EP problem to be able to examine and discuss the results, the EU database[1] is utilized. In the first step, the EU database criteria on energy have to be mapped to the proposed framework in this study. Then, the combination of the methodologies is applied to weigh up the criteria and finally assess 27 countries in the EU between 2015 and 2020. Results are multi-dimensional and can be presented to address various problems.

4.1. Mapping

EU defines its sustainability criteria as aligned with the 17 sustainability goals developed on 2015 by the United Nations (UN), The 7th goal is associated with accessible, affordable, reliable, and sustainable energy. This study utilized this subcategory of the EU database to measure the EP among the EU 27 countries. Thus in this study, the energy criteria presented following the 7th criterion of the sustainability goals in the EU countries are derived from the Eurostat website. Mentioned criteria are presented in Table 2.

The next step is to map the EU indicators with the comprehensive hierarchy of the criteria proposed in this study to evaluate the EP. The mapping procedure is presented in Fig. 2.

Based on the ITARA calculation procedure which is explained in the methodology section, every criterion is clarified as the nature of cost or beneficial. Also, an indifference threshold is proposed based on the deviation of the values beneath the specific criterion in Table 3. If the information would receive from a panel of experts, an indifference threshold could be requested from the experts. However, in this study since EP is calculated through real data retrieved from the EU database,

Table 2
EU energy criteria set.

No	Criteria Code	Name	Unit
1	SDG_07_10	Primary energy consumption	Tonnes of oil equivalent (TOE) per capita
2	SDG_07_11	Final energy consumption	Tonnes of oil equivalent (TOE) per capita
3	SDG_07_20	Final energy consumption in households per capita	Kilogram of oil equivalent (KGOE)
4	SDG_07_30	Energy productivity	Euro per kilogram of oil equivalent (KGOE)
5	SDG_07_40	Share of renewable energy in gross final energy consumption by sector	Percentage
6	SDG_07_50	Energy import dependency by products	Percentage
7	SDG_07_60	Population unable to keep home adequately warm by poverty status	Percentage
8	SDG_13_20	Greenhouse gas emissions intensity of energy consumption	Index, 2000 = 100

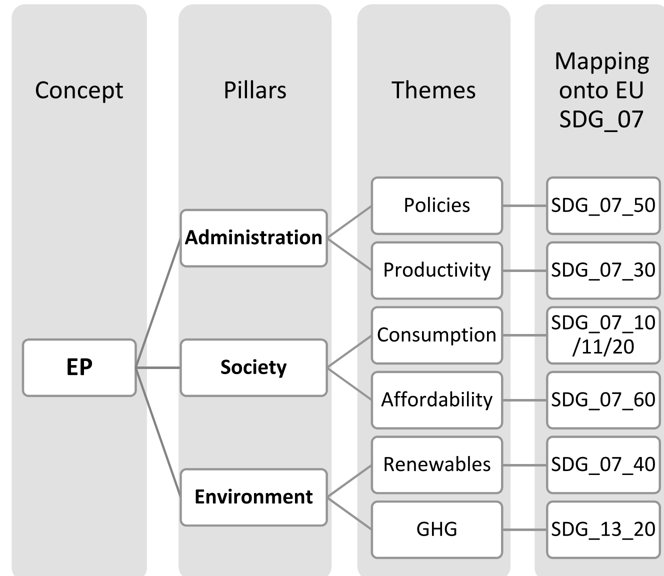

Fig. 2. Mapping EU energy criteria with the novel EP framework.

Table 3
EU energy criteria characteristics for ITARA methodology.

No	Criteria Code	Type	Indifference Threshold
1	SDG_07_10	Cost	0.5
2	SDG_07_11	Cost	0.5
3	SDG_07_20	Cost	50
4	SDG_07_30	Beneficial	1
5	SDG_07_40	Beneficial	5
6	SDG_07_50	Cost	5
7	SDG_07_60	Cost	1
8	SDG_13_20	Cost	5

the indifference threshold is assumed based on the deviation of the data entry among countries and time intervals. For instance, SDG_07_10 is one digit number and varies between 1 and less than 10 while SDG_07_30 is a double-digit and SDGE_07_20 is a three digits number. besides, regarding the range of their deviation indifference threshold is assumed.

5. Discussion

Calculations are done by using the MCDM. app website which is a web application developed by authors to facilitate MCDM calculations and assist researchers in order to mainly focus on their problem instead of struggling with mathematics and calculation processes. The calculations on this web application are validated based on various unit tests in the development phase and later in the production phase in order to ensure accurate results if any modifications would be implemented. However, the calculations of this study are controlled and manually rechecked to ensure the accuracy of the results.

This study proposed a comprehensive definition and inclusive evaluation framework for EP which can be applied to any circumstances. However, the critical issue and a limitation for other studies in this evaluation are accessing the real and accurate input data. In case of lack of data, a panel of professionals and expert judgment can assist managers and decision-makers in the EP evaluations.

5.1. Energy poverty Criteria Assessment

The first step in the case study is to scrutinize criteria along time by

[1] https://ec.europa.eu/eurostat/data/database (Accessed on 24-Nov-22).

applying the ITARA methodology as explained before. These eight criteria are weighted along the time (Table 4).

Results which are presented in Table 4 contains 1269 data entry for 27 countries and 8 criteria between 2015 and 2020. The calculation procedure as an example is summarized in the following (Table 5). Accordingly, the root sum square is calculated as 0.033 and the final weight would be 0.248767.

All the data in Table 4 are represented in Fig. 3 in order to visualize the results over time. As it can be followed, the importance of the criteria is not widely altered in the period of 6 years from 2015 to 2020 and it can be evidence of the accuracy of the results. For instance, the GHG emission criteria (SDG_13_20) had always gained the least weight in the assessment while affordability and final energy consumption (SDG_07_60 and SDG_07_11) had been among the most important criteria all the time in the intended six years studied here.

5.2. European Union Evaluations

There are 27 countries in the EU and the results of their evaluation based on the novel EP framework by applying the MARCOS methodology are presented in Table 6. The table illustrates both countries' weightings and their rank in two different columns for each year from 2015 to 2020. Criteria weights are derived from the calculations from the ITARA methodology resulting from the previous step (Table 4). The final column represents the average weighting among the intended six years and the average ranking based on the calculated weighting values.

Fig. 4 portrays the top-five countries selected based on the average column in Table 6 and describes their trend of outstanding EP performance in EU countries between 2015 and 2020. As it is observable in this figure, Austria is the country with an impressive performance over the past six years. However, Romania has a weaker performance than other competitors among the top 5 countries in the intended time interval. Other countries including Denmark, Sweden, and Estonia had a fluctuation in their performance over the period of six years.

Fig. 5 presents the sorted EU countries regarding the average EP scores in Table 6. This figure seeks to provide information on the overall performance of all EU countries. However, it is unable to depict the fluctuations along the time which results in measuring their performance. Regardless of the top-five countries illustrated in Fig. 4, this figure aims to portray the other 22 countries as well. For instance, Belgium and Cyprus have the weakest EP performance, with a noticeable difference from other countries.

A similar study in the EP literature mainly focused on the social pillar of EP by applying the measurement methodology to 59 developing countries [52]. This study used six dimensions of cooking, appliances, telecommunication, lighting, education, and indoor smoking. This criterion set is recognized as Multidimensional Energy Poverty Index (MEPI) which primarily was developed in 2012 [53]. The MEPI mostly focused on the consumption theme of the social pillar which is presented here in the integrated EP framework in this study. Also, they cover five significant socioeconomic factors including household, wealth, and education to address what is presented as the affordability theme in the social pillar of the integrated EP framework. The study proved the concrete relationship between socioeconomic factors and EP in developing countries. According to this study, affordability and final energy consumption came out as the first two important EP criteria among EU countries which is in line with the mentioned study on the developing countries.

Another similar study on 56 developing countries mostly concentrates on the administration pillar by addressing the strategic position of government in strengthening the population and improving the affordability of the energy in the EP literature [54]. This study combined the

Table 5
ITARA sample calculation for SDG_07_60 on 2020.

Alternatives	α	β	γ	δ
1.5	0.007	0.00722	0.001	0.000
4.1	0.020	0.00867	0.002	0.000
27.5	0.132	0.01059	0.001	0.000
5.7	0.027	0.01156	0.001	0.000
20.9	0.101	0.01300	0.000	0.000
2.2	0.011	0.01300	0.000	0.000
3	0.014	0.01348	0.001	0.000
2.7	0.013	0.01444	0.000	0.000
1.8	0.009	0.01444	0.001	0.000
6.5	0.031	0.01541	0.001	0.000
9	0.043	0.01637	0.001	0.000
17.1	0.082	0.01733	0.002	0.000
4.2	0.020	0.01974	0.000	0.000
3.4	0.016	0.02022	0.007	0.002
3	0.014	0.02744	0.000	0.000
6	0.029	0.02744	0.001	0.000
23.1	0.111	0.02889	0.002	0.000
3.6	0.017	0.03130	0.003	0.000
7.2	0.035	0.03467	0.009	0.004
2.4	0.012	0.04333	0.005	0.000
3.2	0.015	0.04815	0.004	0.000
17.5	0.084	0.05248	0.030	0.025
10	0.048	0.08233	0.002	0.000
5.7	0.027	0.08426	0.016	0.012
2.8	0.013	0.10063	0.011	0.006
10.9	0.052	0.11122	0.021	0.016
2.7	0.013	0.13240		

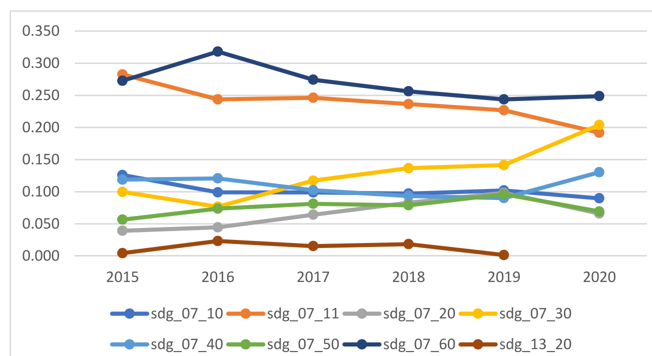

Fig. 3. EU criteria analysis over time.

Table 4
EU criteria analysis.

	2015		2016		2017		2018		2019		2020		Average	
	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank
SDG_07_10	0.126	3	0.099	4	0.099	5	0.097	4	0.102	4	0.090	5	0.102	5
SDG_07_11	0.283	1	0.244	2	0.246	2	0.236	2	0.227	2	0.192	3	0.238	2
SDG_07_20	0.039	7	0.045	7	0.064	7	0.083	6	0.098	5	0.066	7	0.066	7
SDG_07_30	0.100	5	0.077	5	0.117	3	0.137	3	0.141	3	0.204	2	0.129	3
SDG_07_40	0.119	4	0.121	3	0.102	4	0.093	5	0.090	7	0.130	4	0.109	4
SDG_07_50	0.057	6	0.074	6	0.081	6	0.079	7	0.096	6	0.069	6	0.076	6
SDG_07_60	0.273	2	0.318	1	0.274	1	0.256	1	0.244	1	0.249	1	0.269	1
SDG_13_20	0.004	8	0.023	8	0.015	8	0.018	8	0.002	8			0.013	8

Table 6
27 EU countries' evaluation.

	2015		2016		2017		2018		2019		2020		Average	
	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank	W	Rank
AT	0.3971	13	0.4799	7	0.5027	6	0.5500	1	0.5288	4	0.5458	1	0.5007	5
BE	0.2686	27	0.3159	26	0.3089	27	0.3033	27	0.3363	27	0.3082	27	0.3069	27
BG	0.4127	9	0.3820	21	0.3885	23	0.3893	19	0.4018	18	0.3375	21	0.3853	21
HR	0.4478	7	0.4380	9	0.4471	11	0.4328	12	0.4418	12	0.4084	12	0.4360	10
CY	0.3288	24	0.3010	27	0.3216	26	0.3349	26	0.3378	26	0.3316	23	0.3260	26
CZ	0.3270	26	0.3972	15	0.4236	15	0.4080	16	0.4164	15	0.4060	14	0.3964	19
DK	0.4727	3	0.5691	1	0.5830	1	0.5093	3	0.5352	3	0.5115	2	0.5301	1
EE	0.4681	4	0.5361	3	0.5296	3	0.5222	2	0.5486	2	0.4582	6	0.5105	3
FI	0.3938	15	0.5533	2	0.4954	7	0.4683	7	0.4705	8	0.4540	8	0.4726	7
FR	0.3454	22	0.3860	19	0.4037	20	0.3867	21	0.3796	22	0.3624	19	0.3773	23
DE	0.3405	23	0.4010	13	0.4322	13	0.4362	10	0.4605	9	0.3231	24	0.3989	17
EL	0.4058	11	0.3770	22	0.4083	18	0.4249	13	0.4285	14	0.3966	16	0.4069	14
HU	0.3663	19	0.3655	23	0.3844	24	0.3755	24	0.3876	21	0.3524	20	0.3720	24
IE	0.3602	20	0.3836	20	0.4611	8	0.4494	8	0.4537	10	0.5102	3	0.4364	9
IT	0.3775	17	0.3637	24	0.3898	22	0.3878	20	0.3968	19	0.4642	5	0.3966	18
LV	0.4064	10	0.4073	12	0.4073	19	0.3925	17	0.3961	20	0.3888	17	0.3997	16
LT	0.4007	12	0.3594	25	0.3623	25	0.3437	25	0.3491	25	0.3144	26	0.3549	25
LU	0.4371	8	0.4731	8	0.4497	10	0.3825	22	0.3681	23	0.3210	25	0.4053	15
MT	0.4519	5	0.4970	6	0.5121	5	0.4946	5	0.4914	6	0.4552	7	0.4837	6
NL	0.3277	25	0.4280	10	0.4569	9	0.4344	11	0.4034	17	0.4064	13	0.4095	13
PL	0.3922	16	0.3867	18	0.3942	21	0.3788	23	0.4126	16	0.3875	18	0.3920	20
PT	0.4514	6	0.4259	11	0.4430	12	0.4424	9	0.4469	11	0.4233	10	0.4388	8
RO	0.5646	1	0.5187	5	0.5209	4	0.5039	4	0.5125	5	0.4346	9	0.5092	4
SK	0.3674	18	0.3973	14	0.4162	17	0.3906	18	0.3580	24	0.3360	22	0.3776	22
SI	0.3549	21	0.3912	17	0.4192	16	0.4134	14	0.4882	7	0.4218	11	0.4148	11
ES	0.3959	14	0.3944	16	0.4259	14	0.4106	15	0.4361	13	0.3967	15	0.4099	12
SE	0.5428	2	0.5278	4	0.5680	2	0.4925	6	0.5497	1	0.4844	4	0.5276	2

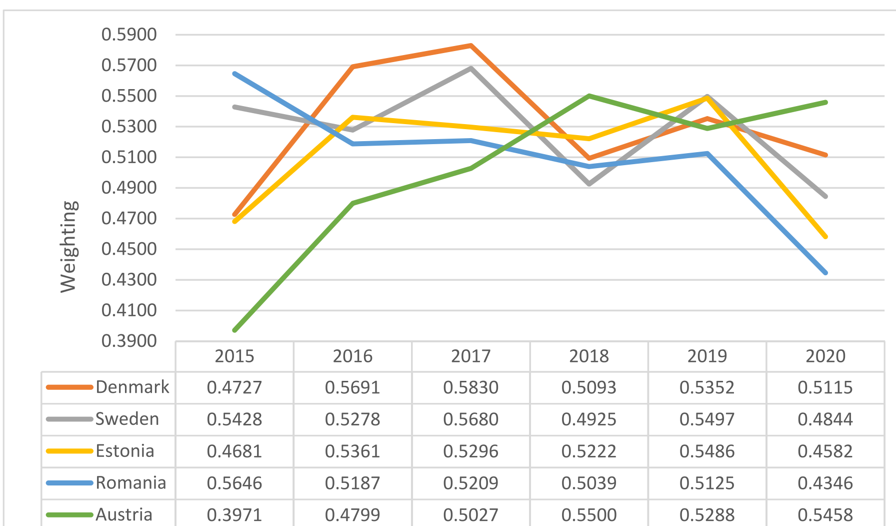

Fig. 4. EU Top-5 countries evaluation.

affordability of energy, which is addressed as fuel poverty in most of the previous studies, with the EP unexpectedly for developing countries which are mostly struggling with the availability of energy. As a consequence, this proves the importance of having a comprehensive approach to measuring EP and also proves that this approach would be independent of the development rate of the intended country.

Another study carried out on fuel poverty resulted in various combinations of family circumstances such as being a single parent with children as more vulnerable cases in fuel poverty and emphasis to take energy efficiency and family circumstances into the account in the policy-making process [55]. This study combines fuel poverty which mainly focuses on affordability with energy efficiency and demonstrates that multi-dimensional metrics would be a more effective approach to measure fuel poverty. This is why this study seeks to have a more comprehensive approach and combine EP, fuel poverty, and sustainability in a single integrated framework.

6. Conclusion

This study focused on the EP in the complicated energy problem environment and aims to describe the previous trends in this concept. In this process, a comprehensive literature review revealed the lack of general consensus among researchers on this issue and its concept. Then, the study presents the inherent complexity of energy problems which adds to the ambiguity of the EP concept. This study in the meanwhile seeks to propose a novel framework for the EP concept in line with the previous studies and adding the sustainability concept which helps develop a comprehensive definition of EP. Since energy in terms of its

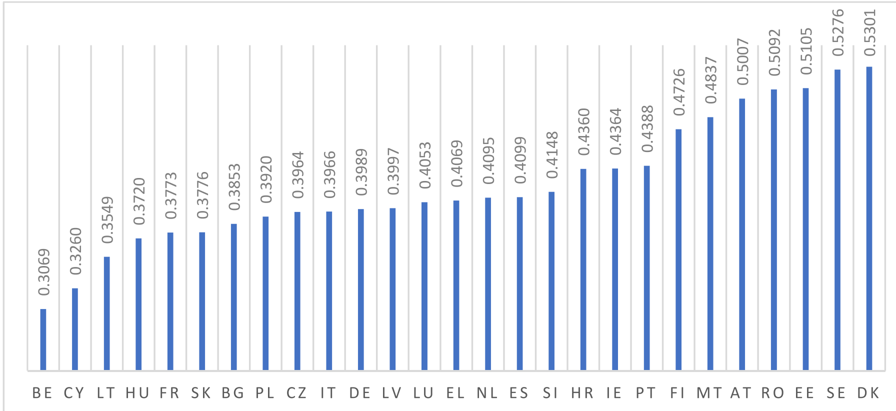

Fig. 5. EP Average weights among 27 members of the EU.

sources and production process, impacts the environment and needs to be sustained among various generations. Thus, this study contributes to the body of knowledge by adding a pillar as a representative of sustainability in the EP definition.

Energy as a criterion recorded among 17 UN sustainability goals with a comprehensive perspective to ensure access to affordable and reliable sources of energy. Subsequently, the EU established its sustainability goals to align with these 17 goals and have comprehensive energy criteria with real data gathered from 2000. In order to apply the proposed EP framework, this study utilized the EU rich database and assessed 27 EU countries between 2015 and 2020. Primarily, the EU energy criteria are mapped to the proposed EP comprehensive framework. Next, two state-of-the-art methodologies with the highest coincidence with the characteristics of the EP problems are proposed and applied to solve the EP problem and result in a variety of useful results presented in figures, and tables.

Results are valuable and beneficial from various perspectives. At first, various categories of EP criteria are evaluated. This evaluation can be regarded both as a pairwise comparison to demonstrate their importance in general and along time from 2015 to 2020 to consider their fluctuations and trends. Next, various countries are evaluated both individually in the previous six years and aggregated over the period of six years. Also, countries can be compared and ranked for each year and on average. Finally, each country can be assessed for each of the EP criteria jointly and severally between 2015 and 2020.

Based on the results, energy consumption was the highly important criterion in the EP framework, and Denmark, Sweden, and Estonia had the most impressive performance among these six years in the field of EP. Also, other countries with their weights and rankings over this period of six years are presented and can be used to assist decision-makers in their decisions to enhance the EP and their performance for future trends. Besides, regarding the incorporation of sustainability as a pillar in EP evaluation, strategic and long-term decisions both for developing and developed nations can be made to assist policy-makers to be more effective in their decisions with a broader perspective.

This EP framework and the proposed combination of methodologies are inclusive and can be applied to other countries as well. Besides, regarding the comprehensive perspective of this framework, it can be applied to evaluate EP for some developing countries. It is anticipated that the criteria weights would vary for other cases based on their own priorities and insecurities in supplying and production of energy sources.

Credit author statement

Hamidreza Hasheminasab: Conceptualization, Methodology, Software, Reviewing and Editing; Dalia Streimikiene: Data curation, Writing – original draft. Mohammad Pishahang: Visualization, Investigation, Software, Validation. Sattar Sattary: Revision and English editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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