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Research paper

Gaussian-based hybrid approach to Entropy for analyzing energy efficiency of emerging economies

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ABSTRACT

This study aims to evaluate energy efficiency in emerging economies. Within this context, a hybrid fuzzy multi-criteria decision-making (MCDM) model is generated. In this model, firstly 7 different criteria that can affect energy efficiency are identified with the help of a comprehensive literature review. After that, these criteria are weighted by considering Gaussian fuzzy Entropy methodology. In the next stage, emerging 7 (E7) countries are ranked regarding the performance of energy efficiency with Gaussian fuzzy the interactive multi-criteria decision-making (TODIM) approach. In the final stage, the criteria have also been evaluated by using fuzzy decision-making trial and evaluation laboratory (DEMATEL) method for robustness check. Similarly, the alternatives are also ranked by using technique for order preference by similarity to ideal solution (TOPSIS) to evaluate the coherency of the analysis results. Finally, the calculations are also made with triangular and trapezoidal fuzzy numbers to control the reliability of the proposed model. The findings indicate that economic development and technological competency are the main factors that influence energy efficiency. Moreover, it is also stated that Russia and Brazil are the most successful countries in energy efficiency whereas India and Turkey are in the last places. Therefore, these issues can be helpful to minimize the costs of energy usage for these countries

1. Introduction

While the need for global energy is constantly increasing, energy resources are decreasing. Therefore, after a certain time, there is a risk that the energy sources will not meet the need (Wen et al., 2021). As a result, people will not be able to satisfy their basic needs and shrinkage will occur in industrial production. Within this framework, the country will suffer both socially and economically. It is obvious that the efficient use of energy resources is of great importance (Figus et al., 2020). The goal in energy efficiency is to transform each unit of energy into more services and products. In other words, energy efficiency means doing the same job by using less energy.

There are a number of strategies that can be applied to ensure energy efficiency. Within this context, one of the most important strategies is energy saving. The main purpose of this situation is to reduce the amount of energy spent at each stage to realize a certain amount of production and service (Ahmed et al., 2020). Many different factors must be considered at the same time to achieve this objective. As an example, the technological infrastructure of the country is vital in this process. In this scope, it is possible to learn applications that can contribute to energy efficiency through research and development (Shen and Lin, 2020). In addition, machines that consume less energy will contribute to saving energy (Neij et al., 2021).

Furthermore, state support is another issue which plays a significant role in this process. In this context, many government incentives such as low interest loans can contribute to energy efficiency (Forrester and Reames, 2020). On the other hand, the legal infrastructure of the country is also essential in this process. For example, fines, sanctions, and adequacy of legislation will lead individuals and institutions to save energy (Mohsin et al., 2021). Another important issue in this process is the consumption habits of the people (Xie et al., 2020). Within this framework, it is necessary to carry out awareness-raising activities throughout the country. If the energy resources are insufficient, it can be possible to increase the energy savings by competently explaining the problems to citizens (Han et al., 2021).

Renewable energy sources are another issue that can contribute to the energy efficiency. Renewable energies are energy types that provide their resources from nature, such as sun and wind (Zhao et al., 2021). Hence, it can be understood that their raw materials will never run out, and, in the long term, it may

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be possible to provide energy at a lower cost thanks to the use of these energy sources (Li et al., 2021a). Moreover, the use of these energy resources will reduce the countries' dependence on foreign energy (Liu et al., 2021). On the other hand, economic development will also contribute to the efficient use of energies (Akram et al., 2020). In other words, a country that has increased its economic power can more clearly take these steps to use energy efficiently.

Additionally, it is very important to ensure energy efficiency, accordingly many factors need to be simultaneously examined to achieve this goal. For this purpose, the analysis method to be applied is also significant. Otherwise, the accuracy of the analysis results obtained will be questioned. MCDM methods are also the approaches used to identify the most important factors among the different criteria, such as DEMATEL, analytic hierarchy process (AHP) and analytic network process (ANP) (Mao et al., 2020; İç, 2020). These methods are also taken into consideration, especially in recent years, depending on the fuzzy logic (Akram et al., 2021; Lam et al., 2021). In this way, it can also be possible to minimize the uncertainties encountered in the decision-making process (Kumar and Barman, 2021).

In this study, the factors affecting energy efficiency in E7 countries are examined. In this context, first, similar studies in the literature are examined and 7 different criteria have been determined. Gaussian fuzzy Entropy approach is taken into consideration in determining the importance weights of these criteria. After that, E7 countries are listed with respect to their success in energy efficiency. In this analysis, Gaussian fuzzy TODIM model is considered. For robustness check, the criteria have also been evaluated by using fuzzy DEMATEL methodology. Similarly, the alternatives are also ranked with TOPSIS to evaluate the coherency of the analysis results. Another robustness check is also performed by making analysis with triangular and trapezoidal fuzzy numbers.

Entropy methodology is very popular in the literature. This approach is mainly considered to measure uncertainty. It was firstly taken into consideration in the studies related to physics and mathematics (Sreeparvathy and Srinivas, 2020). The main purpose of this approach is to weigh different factors according to their importance (Zeng et al., 2020), and it can be defined as the measurement of uncertainty in information. The main advantage of the Entropy approach is that as this approach is a knowledge-based weighting method, it is accepted that weighting is done objectively (Kumar et al., 2020). On the other hand, since the analyzes in this method are done through alpha cut, it is possible to make any fuzzy numbers (Gao et al., 2020). Furthermore, because the calculation can be conducted for each level of alpha cut, it can also be used for asymmetric fuzzy numbers (Abd Elaziz et al., 2020).

It is possible to mention many different advantages of this study. Firstly, a comparative analysis has been made by using fuzzy Entropy and fuzzy DEMATEL methods in determining the importance weights of the criteria. These different analyzes provide an opportunity to make a robustness check with respect to the results. Additionally, the countries are also ranked by both TODIM and TOPSIS approaches so that the coherency and the reliability of the results can be evaluated. Furthermore, in this study, a comprehensive literature analysis has been made and a list of criteria that could affect energy efficiency has been created. This set of criteria is guiding for both those working in the market and academics. One of the biggest innovations of the study is the use of Gaussian fuzzy numbers in the analysis process. Moreover, all calculations have been made by considering 3 different fuzzy numbers.

The rest of the study is organized as following. The second part includes the literature review in which similar studies are evaluated. On the other hand, the third part gives information about the theoretical background of the methods used in the analysis process. Furthermore, the fourth part explains the analysis results. Additionally, the discussion and conclusion take place in the fifth section.

2. Literature review

In this section, firstly, literature on the energy efficiency is evaluated. After that, the literature review regarding the methodology is shared. Finally, the results of the literature review are discussed.

2.1. Literature on energy efficiency

The issue of energy efficiency is handled by many different authors in the literature. In this regard, many studies focused on how to increase energy efficiency in general. It has been argued that the use of renewable energy will increase energy efficiency in a significant part of the studies. Renewable energies are energy types that take their source from nature (Chachuli et al., 2021). Therefore, the sources of these energy types are not exhausted (Garrett-Peltier, 2017). Moreover, it is believed that with these alternative methods, energy can be provided at a lower cost in the long run (Saprykina, 2021; Dell'Anna, 2021). Bayar and Gavriletea (2019) focused on the relationship between energy efficiency and renewable energy in developing countries. In this study, data between 1992 and 2014 were analyzed by Westerlund cointegration and Dumitrescu Hurlin panel causality tests. It is determined that there was a relationship between the specified variables. Moreover, Zhu et al. (2020) studied the same issue for Japan. It has been determined that the use of renewable energy plays an important role in energy efficiency. Apak et al. (2017) emphasized the importance of the same concern for Turkey.

Furthermore, many researchers have also determined that technological investment has an important role in energy efficiency. Within this context, if a country can follow and apply technological developments, they can use energy more efficiently (Gupta et al., 2017; Chen et al., 2021). Within this framework, the use of products with less energy consumption will help to save significantly (Du et al., 2021). On the other hand, research and development studies can also provide new opportunities to reduce energy use (Mohsin et al., 2021). Cantore et al. (2016) focused on how to improve energy efficiency in 29 developing countries. It is concluded that the technological infrastructure of the country should be substantial to use the energy more efficiently. In addition, Zhang et al. (2017) also carried out a study on how to develop the iron and steel industry in China using regression analysis. As a result, it is determined that countries with advanced technology use energy more efficiently.

Many studies have also emphasized that government incentives are very important in the efficient use of energy. When governments give low interest loans, companies are encouraged to invest in energy efficiency (Carbonara and Pellegrino, 2018a; Lyulyov et al., 2021). On the other hand, tax reductions can also be a very important application that will contribute to achieve this goal (Alam et al., 2019; Adua, 2021). As an example, Gooding and Gul (2017) conducted a study on energy efficiency in England. In this process, a semi-structured interview method was considered. As a result, it was concluded that the financial support of governments has a very important role in this process. On the other hand, improving the consumption habits of individuals has also been emphasized by many different researchers (Babatunde et al., 2021; Zekić-Sušac et al., 2021). According to these studies, if the level of awareness in humans regarding excess energy use is increased it will be possible to save energy (Wang et al., 2019; Nakano and Washizu, 2018).

On the other side, some researchers have argued that there is a positive relationship between economic development and energy efficiency. If a country develops economically, it will be able to carry out research and development activities more effectively (Dabbous and Tarhini, 2021; Baloch et al., 2021). Within this context, they will be able to follow current technological developments more quickly (Pan et al., 2019; Adua et al., 2021). As a result, it will be possible to use energy more effectively. In this framework, Balitskiy et al. (2016) focused on the relationship between economic growth and energy efficiency in European Union countries. In this study, where regression analysis was conducted, it was stated that economic growth was an important variable in energy efficiency. In addition, Yang and Wei (2019) examined energy efficiency in China with the help of a data envelopment method and achieved the same result. In addition to the studies mentioned, some researchers also stated that the legal infrastructure (Biresselioglu et al., 2017; Barkhordar et al., 2018) and qualified personnel (Plitsos et al., 2017; Neef et al., 2019; Han et al., 2021) also play an important role in energy efficiency.

2.2. Literature on methodology

With respect to the literature review related to the methodology, it is identified that there are lots of studies in which MCDM methods are taken into consideration. Some researchers used these methods on their original forms, whereas some others considered them with fuzzy logic (Çalık, 2021; Rehman and Ali, 2021; Solangi et al., 2021). On the other side, there are also some studies in which some of these approaches are used in a hybrid way. For instance, Chen et al. (2020), Bostancı and Erdem (2020) and Tirkolaee et al. (2020) used both DEMATEL and TOPSIS methods in their studies to reach the objective. Additionally, Elimination Et Choix Traduisant la Realité (ELECTRE) approach was also considered with other approaches, such as VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Çalı and Balaman, 2019), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Gul et al., 2018) and Delphi (Kumar et al., 2017). Furthermore, Joshi (2020) made an analysis with Entropy and TOPSIS approaches together in the evaluation process.

2.3. Literature review results

According to the results of the literature review, it is understood that the subject of energy efficiency is very popular in the literature. Lots of these studies mainly focused on ways to increase the efficiency in energy use. Moreover, it is also seen that different approaches were considered in these studies, such as regression and data envelopment analysis. The main missing part in the literature is that numerical variables are generally taken into consideration to evaluate energy efficiency. Therefore, there is a need for a new study which considers both numerical and non-numerical variables at the same time. Hence, it is thought that different methodologies should be considered to achieve this objective. For this purpose, fuzzy DEMATEL and fuzzy Entropy approaches are taken into consideration in determining the importance weights of these criteria for energy efficiency. In addition to this issue, E7 countries are ranked for their success in energy efficiency by using fuzzy TODIM and fuzzy TOPSIS. On the other side, triangular, trapezoidal and Gaussian fuzzy numbers are used separately in all analyzes. With the help of these issues, a wide criteria set can be taken into account in the analysis process so that more appropriate results can be obtained. Therefore, it is believed that this study makes a significant contribution to the energy efficiency literature.

3. Proposed methodology

In this section, first, mathematical operations of the proposed model are explained. Later, the novelties of this model are discussed.

3.1. Mathematical operations

This study aims to evaluate the significant factors of energy efficiency. The analysis process includes two different stages. Firstly, important criteria are identified and weighted by Gaussian fuzzy Entropy. In the second stage, Gaussian fuzzy TODIM method is considered to rank E7 economies. Entropy was first used in physics as a measurement of uncertainty. Later, this method was also expressed mathematically by Shannon. After that, it started to be used in many fields, especially computer science (Sahin and Yip, 2017). Entropy method is a weighting method based on uncertainty. The steps of the fuzzy entropy method are given below. The decision matrix ($\tilde{Z}$) is created by taking the average of the fuzzy values of expert opinions. This process is expressed in Eqs. (1) and (2). In these equations, $\tilde{z}_{ij}$ represents the significance of the criterion i in comparison with criterion j. On the other side, n gives information about the number of the experts.

$$\tilde{Z} = \begin{bmatrix} 0 & \tilde{z}_{12} & \cdots & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \cdots & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & \cdots & 0 \end{bmatrix} \tag{1}$$

$$\tilde{Z} = \frac{\tilde{Z}^1 + \tilde{Z}^2 + \tilde{Z}^3 + \cdots \tilde{Z}^n}{n} \tag{2}$$

Alpha section equations of fuzzy numbers ($Z_\propto$) in the generated decision matrix are obtained with the help of Eq. (3). In this process, the alpha value ($\propto$) can become between 0 and 1 (Lotfi and Fallahnejad, 2010). In this equation, $z(\propto)^l$ represents lower limit of $Z_\propto$ whereas the upper limit is defined as $z(\propto)^u$. On the other side, μ demonstrates the mean value of Gauss fuzzy numbers and σ shows the standard deviation of these numbers.

$$Z_\propto = \left[z(\propto)^l, z(\propto)^u\right] = \left[\mu - \sigma\sqrt{-\ln(\propto)}, \mu + \sigma\sqrt{-\ln(\propto)}\right] \tag{3}$$

Then, the decision matrix is normalized by dividing the expressions obtained with alpha section equations into the sum. Within this framework, the upper limit and the lower limit of the alpha sections are normalized with Eqs. (4) and (5). As a result of the calculations, the normalized matrix (P) is obtained (Lotfi and Fallahnejad, 2010). In this framework, p_{ij}^l and p_{ij}^u give information about lower and upper limits of P.

$$p_{ij}^l = \frac{z_{ij}^l}{\sum_{j=1}^m z_{ij}^u} \quad j = 1, \ldots, m i = 1, \ldots, n \tag{4}$$

$$p_{ij}^u = \frac{z_{ij}^u}{\sum_{j=1}^m z_{ij}^u} \quad j = 1, \ldots, m i = 1, \ldots, n \tag{5}$$

In the next step, the entropy values of the criteria in the normalized P=[p_{ij}] matrix are calculated. In this calculation, the lower and upper boundary entropies (h_i^l *and* h_i^u) of the criteria are determined using Eqs. (6)–(8). In the calculation, when p_{ij} is equal to 0, $\ln p_{ij}$ is taken as 0. In these equations, the number of the criteria are defined as m.

$$h_i^l = min\left\{-h_0\sum_{j=1}^m p_{ij}^l lnp_{ij}^l, -h_0\sum_{j=1}^m p_{ij}^u lnp_{ij}^u\right\} i = 1, \ldots, n \tag{6}$$

$$h_i^u = max\left\{-h_0\sum_{j=1}^{m}p_{ij}^l lnp_{ij}^l, -h_0\sum_{j=1}^{m}p_{ij}^u lnp_{ij}^u\right\} i = 1,\ldots,n \tag{7}$$

$$h_0 = \frac{1}{\ln(m)} \tag{8}$$

Upper and lower diversifications ($d_i^l and d_i^u$) are identified from the calculated entropy values with the help of Eq. (9).

$$d_i^l = 1 - h_i^u \quad d_i^u = 1 - h_i^l i = 1,\ldots,n \tag{9}$$

The upper and lower weights ($w_i^l and w_i^u$) of the criteria are calculated by Eq. (10) (Aytekin and Karamaşa, 2017).

$$w_i^l = \frac{d_i^l}{\sum_{s=1}^{n} d_s^u} w_i^u = \frac{d_i^u}{\sum_{s=1}^{n} d_s^l} \quad i = 1,\ldots,n \tag{10}$$

Entropy methodology was used in the literature for many different purposes. For instance, Narayanamoorthy et al. (2019) aimed to make an analysis for robot selection. The importance of the criteria in this study is defined with the help of fuzzy entropy approach. In addition to this study, Cao et al. (2019) focused on migraine patients by using this methodology. On the other side, Liang et al. (2019) tried to identify the factors which influence the website quality of internet banking. In this study, the analysis is conducted by using the fuzzy entropy method. In addition to this study, there are also some studies in which fuzzy entropy methodology is considered for the energy industry. In this context, Qin et al. (2019) examined wind energy projects and Cavallaro et al. (2019) evaluated solar power technologies with the help of this approach.

On the other side, Gaussian fuzzy TODIM is considered to rank E7 economies regarding the energy efficiency. In this context, it evaluates the criteria according to their superiority, and it is a more preferred method among other alternatives — more than decision making methods in literature. This methodology is mainly preferred to rank different alternatives. In this method, the decision matrix is created first with the help of Eqs. (11) and (12). In these equations, $\tilde{x}_{ij}$ shows the importance of the alternative i in comparison with criterion j. Additionally, n states the number of the experts.

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{11}$$

$$\tilde{X} = \frac{\tilde{x}^1 + \tilde{x}^2 + \tilde{x}^3 + \cdots \tilde{x}^n}{n} \tag{12}$$

From this decision matrix, the distances of each alternative from the others are defined as $d\left(\tilde{A}, \tilde{B}\right)$.These values are calculated by Eq. (13). In addition, μ_1 and μ_2 indicate the mean values of the Gauss fuzzy numbers regarding the first and second alternatives. Also, σ_1 and σ_2 give information about the standard deviations of the Gauss fuzzy numbers as for these alternatives.

$$d\left(\tilde{A}, \tilde{B}\right) = \sqrt{1 - \sqrt{\frac{2\sigma_1\sigma_2}{\sigma_1^2 + \sigma_2^2}} e^{\frac{-0,25(\mu_1-\mu_2)^2}{\sigma_1^2+\sigma_2^2}}} \tag{13}$$

By considering these distances, gain and loss values (G and L) are calculated. For benefit criteria, equations (14) and (15) are used. On the other side, regarding the cost criteria, Eqs. (16) and (17) are taken into consideration (Zhang and Fan, 2011).

$$G_{ik}^j = \begin{cases} d\left(\widetilde{x_{ij}}, \widetilde{x_{jk}}\right) & \widetilde{x_{ij}} \geq \widetilde{x_{jk}} \\ 0 & \widetilde{x_{ij}} < \widetilde{x_{jk}} \end{cases} \tag{14}$$

$$L_{ik}^j = \begin{cases} 0 & \widetilde{x_{ij}} \geq \widetilde{x_{jk}} \\ -d\left(\widetilde{x_{ij}}, \widetilde{x_{jk}}\right) & \widetilde{x_{ij}} < \widetilde{x_{jk}} \end{cases} \tag{15}$$

$$G_{ik}^j = \begin{cases} 0 & \widetilde{x_{ij}} \geq \widetilde{x_{jk}} \\ d\left(\widetilde{x_{ij}}, \widetilde{x_{jk}}\right) & \widetilde{x_{ij}} < \widetilde{x_{jk}} \end{cases} \tag{16}$$

$$L_{ik}^j = \begin{cases} -d\left(\widetilde{x_{ij}}, \widetilde{x_{jk}}\right) & \widetilde{x_{ij}} \geq \widetilde{x_{jk}} \\ 0 & \widetilde{x_{ij}} < \widetilde{x_{jk}} \end{cases} \tag{17}$$

Then, the relative weights (w) are calculated by using Eqs. (18) and (19).

$$w_{jr} = \frac{w_j}{w_r} \tag{18}$$

$$w_r = \max\left(w_j\right) \tag{19}$$

With these weights, the dominance value (δ) of each alternative (A_i) to the other alternative (A_j) is calculated with the help of Eqs. (20) and (21) (Krohling and de Souza, 2012). In this scope, θ defines the attenuation factor of the losses.

$$\delta\left(A_i, A_j\right) = \sum_{c=1}^{m} \phi_c\left(A_i, A_j\right) \tag{20}$$

$$\phi_c\left(A_i, A_j\right) = \begin{cases} \sqrt{\frac{w_{jc}G_{ik}^j}{\sum w_{jc}}} forGain \\ \frac{-1}{\theta}\sqrt{\frac{\left(\sum w_{jc}\right)\left(-L_{ik}^j\right)}{w_{jc}}} forLoss \end{cases} \tag{21}$$

The overall value (ξ) of alternative A_i is calculated and sorted from the calculated dominance values by Eq. (22) (Wang and Liu, 2017).

$$\xi\left(A_i\right) = \frac{\sum_{k=1}^{m}\delta_{ik} - \min(\sum_{k=1}^{m}\delta_{ik})}{\max\left(\sum_{k=1}^{m}\delta_{ik}\right) - \min(\sum_{k=1}^{m}\delta_{ik})} \tag{22}$$

Additionally, Eq. (23) is used to compare two Gaussian fuzzy numbers (Liu et al., 2012). This equation is given for any two probability distributions and can be used in Gaussian. In this equation, X_1 and X_2 are random variables. On the other side, respectively f_1 and f_2 represent relative distribution of these variables.

$$d_{f_1 > f_2} = P\left(X_1 \geq X_2\right) - 0,5P\left(X_1 = X_2\right) \tag{23}$$

3.2. Novelties of the proposed model

In this study, we proposed a hybrid fuzzy MCDM model to evaluate energy efficiency for E7 economies. This proposed model has two different phases. Firstly, 7 different criteria that can affect energy efficiency have been weighted. In this framework, Gaussian fuzzy Entropy approach is taken into consideration. In the second stage, E7 economies are ranked with Gaussian fuzzy TODIM methodology. In addition to this situation, for robustness check, the criteria have also been evaluated by using fuzzy DEMATEL method. Similarly, the alternatives are also ranked with TOPSIS to evaluate the coherency of the analysis results. Another robustness check is also performed by making analysis with triangular and trapezoidal fuzzy numbers.

It is possible to mention some novelties of this proposed model. In this proposed model, a hybrid methodology is taken into consideration. There are also non-hybrid MCDM models in the literature (Zamani and Berndtsson, 2019; Chmielarz and Zborowski, 2018). In these models, generally only one MCDM model is considered to rank different alternatives. However, the weights of the criteria are defined by the authors subjectively (Nanayakkara et al., 2020; Chitnis and Vaidya, 2018). On the other side, in the hybrid models, different MCDM approaches are taken into consideration in both phases. Thus, it is obvious that hybrid model becomes helpful to reach more objective results.

Considering the Entropy approach in the calculation of the importance weights of the criteria provides some advantages. The most important advantage of the entropy weighting method is that it reduces the subjective influence of decision makers in the analysis process (Cao and Lin, 2017). In the calculations made by this method, the uncertainty measurement in the criteria is taken into account (Versaci and Morabito, 2021). Therefore, the Entropy method contributes to the calculations to be made more objectively (Deng et al., 2018). Similarly, using the DEMATEL approach in this process provides some advantages. Thanks to this method, the causality relationship between the criteria can also be taken into consideration (Abdullah et al., 2019; Seker and Zavadskas, 2017). However, these issues have not been considered in models where these methods are not used (Lyu et al., 2020; Solangi et al., 2019; Darko et al., 2019; Mavi and Standing, 2018; Ervural et al., 2018).

Moreover, considering TODIM and TOPSIS methodologies in the process of ranking E7 countries provide some advantages, as well. Within this context, the potential value of gains and losses can be considered in TODIM so that the risk preferences can be reflected more appropriately (Chen and Goh, 2019). Another important superiority of this methodology is that the experts' bounded rational behavior characteristic can be taken into consideration (Li et al., 2018). Additionally, TOPSIS method has some benefits in comparison with other similar approaches. For instance, the distances to both positive and negative ideal solutions can be considered in the analysis process (Alaa et al., 2019; Suthar and Gadit, 2019). On the other side, in the models of Chen (2018), Ren et al. (2017), Liang et al. (2019) and Meksavang et al. (2019), only the distance to positive ideal solution is taken into account.

The use of Gaussian fuzzy numbers in the analysis process is also accepted as an important novelty of the study. The complexity of the problems in decision-making processes significantly increases the need for new methods. In this context, MCDM models are often considered with triangular and trapezoidal fuzzy numbers. In this way, it was aimed to manage uncertainties in decision-making processes more effectively (Seresht and Fayek, 2019). On the other hand, triangular and trapezoidal fuzzy numbers constitute a membership value for a certain interval (Faizi et al., 2020). On the other hand, in other cases, the membership value is considered as 0 (Dombi and Jónás, 2020). In other words, situations out of range are not taken into consideration in the analysis (Ayyildiz et al., 2020). Since Gauss numbers are continuous, they can take into account the likelihood for all situations (Tolga et al., 2020; Sahin and Yip, 2017). Therefore, since Gaussian fuzzy considers the certainty of numbers in a wider area, it is possible to determine the values of the weights more realistically (Kumar et al., 2021; Leite et al., 2020).

Furthermore, this proposed model is also appropriate for the purpose of the study. In this study, the influencing factors of the energy efficiency are evaluated, such as technological competence and government support. These factors may affect each other significantly. Because of this situation, considering Entropy and DEMATEL methodology to weight the items can provide essential advantages. In addition to this issue, a comparative evaluation is made to rank E7 countries by considering both TODIM and TOPSIS approach. This situation provides an opportunity to check the reliability and consistency of the analysis results. On the other hand, with the help of making sensitivity analysis by considering 7 different conditions, the validity of the proposed model can be measured. Nevertheless, the biggest limitation of this proposed model is that pattern recognition methodology is not taken into account. Because of this situation, the expert team could not leave the questions asked to them blank. Instead, this team is expected to evaluate even issues on which it had relatively little opinion.

4. Analysis results

In this part of the study, firstly, the criteria, which have an influence on energy efficiency, are identified. After that, they are weighted with Gaussian fuzzy entropy approach. In the third stage, E7 economies are ranked with Gaussian fuzzy TODIM. In the final part, robustness check has been performed by considering fuzzy DEMATEL and fuzzy TOPSIS methods. Moreover, analysis results with triangular and trapezoidal fuzzy numbers are also shared. Finally, a sensitivity analysis has been performed by considering 7 different conditions.

4.1. Weighting the criteria

While defining the influencing criteria of energy efficiency, the literature review has been taken into consideration. As a result of comprehensive literature evaluation, 7 different criteria that can affect energy efficiency have been determined. The details of these criteria and their supported literature are given in Table 1.

One of the fundamental criteria for using energy more efficiently is technological competence. Within this context, it is significant to invest in research and development, to isolate buildings, and to choose machines that use less energy (Cantore et al., 2016; Zhang et al., 2017; Carbonara and Pellegrino, 2018a). Government support is another factor that plays a crucial role in this framework. Owing to government incentives, such as providing low interest loans, more efficient use of energy can be provided (Alam et al., 2019; Gooding and Gul, 2017). People's consciousness can also contribute to the efficient use of energy. Issues such as improving consumption habits are very significant in this process (Wang et al., 2019; Nakano and Washizu, 2018). The use of renewable energy has also positive impact on the effectiveness of the energy. With these energy types, it is possible to provide energy without polluting the environment (Garrett-Peltier, 2017; Bayar and Gavriletea, 2019; Zhu et al., 2020). Also, since these energies take their source from nature, there is no risk of depleting the resources. As can be seen from the literature review, countries with high economic development are more successful in energy efficiency (Pan et al., 2019; Balitskiy et al., 2016; Yang and Wei, 2019). In this framework, the growth in gross domestic products can be accepted as the improvement in the economy. The main reason is that countries with high development attach more importance to energy efficiency. Another important factor in this process is that the legal infrastructure should be sufficient. Laws to be enacted to use energy more efficiently contribute to the development of this process (Biresselioglu et al., 2017; Barkhordar et al., 2018). The last important point is the competence of employees. Employment of personnel with a high level of knowledge for efficient use of energy will also help achieve this goal (Biresselioglu et al., 2017; Barkhordar et al., 2018).

In order to calculate the weights of these criteria, opinions are provided from three different experts. The experts have at least 10 years of experience regarding energy investment companies. They are the top managers of these companies and they have PhD degree. These people have a lot of academic papers regarding energy economics. Then, the decision matrix is created with the average of expert opinions. In this process, the Entropy method is taken into account. At this stage, the evaluations of the experts are converted into the linguistic expressions given in Table 2 (He et al., 2017; Peña et al., 2019; Lourenzutti and Krohling, 2014).

On the other hand, the decision matrix, in which the average values of the opinions are considered, is shown in Table 3.

The normalized matrix of the alpha section matrix calculated for alpha = 0.5, with the help of Eqs. (1)–(3). After that, diversification and weights are calculated with Eqs. (4)–(10). The results are demonstrated on Table 4.

Table 1
The list of the factors affecting energy efficiency.

Criteria	Supported Literature
Technological Competence (C1)	Cantore et al. (2016); Zhang et al. (2017); Carbonara and Pellegrino (2018b)
Government Support (C2)	Alam et al. (2019); Gooding and Gul (2017)
People's Consciousness (C3)	Wang et al. (2019); Nakano and Washizu (2018)
Renewable Energy Usage (C4)	Garrett-Peltier (2017); Bayar and Gavriletea (2019); Zhu et al. (2020)
Economic Development (C5)	Pan et al. (2019); Balitskiy et al. (2016); Yang and Wei (2019)
Legal Sufficiency (C6)	Biresselioglu et al. (2017); Barkhordar et al. (2018)
Qualified Employee (C7)	Plitsos et al. (2017); Neef et al. (2019)

Table 2
Linguistic variables.

Weights	Ratings	Fuzzy Numbers
Very low	Unimportant	Gaussian (x, 1, 0.5)
Low	Moderately important	Gaussian (x, 3, 0.5)
Average	Important	Gaussian (x, 5, 0.5)
High	Very important	Gaussian (x, 7, 0.5)
Very high	Extremely important	Gaussian (x, 9, 0.5)

Table 3
Decision matrix for Gaussian fuzzy numbers.

c1		c2		c3		c4		c5		c6		c7	
0	0	3,92	4,75	4,58	5,42	5,25	6,08	7,92	8,75	8,58	9,42	6,58	7,42
6,58	7,42	0	0	3,92	4,75	4,58	5,42	3,92	4,75	4,58	5,42	5,25	6,08
3,92	4,75	3,25	4,08	0	0	4,58	5,42	4,58	5,42	5,25	6,08	6,58	7,42
6,58	7,42	4,58	5,42	3,25	4,08	0	0	3,92	4,75	5,92	6,75	4,58	5,42
7,92	8,75	7,92	8,75	7,92	8,75	8,58	9,42	0	0	4,58	5,42	3,92	4,75
5,25	6,08	3,92	4,75	4,58	5,42	6,58	7,42	6,58	7,42	0	0	6,58	7,42
6,58	7,42	7,25	8,08	3,25	4,08	4,58	5,42	4,58	5,42	6,58	7,42	0	0

Table 4
Entropy, diversification and weights (Alpha = 0,5).

Gaussian	C1		C2		C3		C4		C5		C6		C7	
H	0,85	0,91	0,85	0,91	0,84	0,91	0,84	0,91	0,86	0,9	0,85	0,91	0,85	0,91
D	0,09	0,15	0,09	0,15	0,09	0,16	0,09	0,16	0,1	0,14	0,09	0,15	0,09	0,15
W	0,09	0,24	0,08	0,24	0,08	0,25	0,08	0,25	0,09	0,23	0,08	0,23	0,09	0,24

Table 5
Alpha section weights.

Alpha	C1		C2		C3		C4		C5		C6		C7	
0,1	0,07	0,31	0,06	0,33	0,06	0,34	0,06	0,34	0,07	0,3	0,06	0,31	0,06	0,32
0,2	0,07	0,28	0,07	0,3	0,07	0,31	0,07	0,31	0,07	0,27	0,07	0,28	0,07	0,29
0,3	0,08	0,26	0,07	0,28	0,07	0,28	0,07	0,28	0,08	0,25	0,07	0,26	0,08	0,27
0,4	0,08	0,25	0,08	0,26	0,08	0,27	0,08	0,27	0,08	0,24	0,08	0,24	0,08	0,26
0,5	0,09	0,24	0,08	0,24	0,08	0,25	0,08	0,25	0,09	0,23	0,08	0,23	0,09	0,24
0,6	0,09	0,22	0,09	0,23	0,09	0,23	0,09	0,23	0,1	0,22	0,09	0,22	0,09	0,23
0,7	0,10	0,21	0,09	0,21	0,09	0,22	0,1	0,22	0,1	0,21	0,09	0,2	0,1	0,21
0,8	0,11	0,2	0,1	0,19	0,1	0,2	0,1	0,2	0,11	0,19	0,1	0,19	0,11	0,2
0,9	0,12	0,18	0,11	0,18	0,11	0,18	0,11	0,18	0,12	0,18	0,11	0,17	0,12	0,18
1	0,15	0,15	0,13	0,13	0,14	0,14	0,14	0,14	0,15	0,15	0,14	0,14	0,15	0,15

Table 6
Weights of the criteria.

Criteria	Weights
Technological Competence (C1)	0.1501240661
Government Support (C2)	0.134761847
People's Consciousness (C3)	0.139476786
Renewable Energy Usage (C4)	0.141656456
Economic Development (C5)	0.150729964
Legal Sufficiency (C6)	0.136111461
Qualified Employee (C7)	0.147139421

Moreover, other alpha sections other than alpha = 0.5 were also calculated. The calculated weights for all alpha cuts are shown in Table 5.

On the other side, the weights of the criteria are given on Table 6.

Table 6 indicates that economic development and technological competence are the most significant criteria. Moreover, government support and legal sufficiency play a lower role for this situation in comparison with other factors.

4.2. Ranking E7 economies regarding energy efficiency

The criteria weighted by the entropy method are used to rank the E7 (Brazil (E1), China (E2), India (E3), Indonesia (E4), Mexico (E5), Russia (E6), Turkey (E7)) countries. Expert opinions are converted into a decision matrix with the help of Eqs. (11) and (12). The decision matrix is shown in Table 7.

Additionally, the distances of the countries according to the C1 criteria are given in Table 8. Similarly, distances are also calculated for other 7 criteria. In the TODIM method, the positive criteria are taken into consideration with equations (14) and (15).

Table 7
TODIM decision matrix.

E1		E2		E3		E4		E5		E6		E7	
4	0,5	5	0,5	6	0,5	6	0,5	5	0,5	4	0,5	6	0,5
5	0,5	5	0,5	8	0,5	7	0,5	5	0,5	5	0,5	6	0,5
5	0,5	7	0,5	6	0,5	5	0,5	5	0,5	6	0,5	6	0,5
6	0,5	6	0,5	5	0,5	5	0,5	6	0,5	4	0,5	6	0,5
4	0,5	6	0,5	6	0,5	4	0,5	5	0,5	4	0,5	6	0,5
6	0,5	6	0,5	6	0,5	4	0,5	6	0,5	4	0,5	6	0,5
4	0,5	4	0,5	6	0,5	6	0,5	6	0,5	6	0,5	7	0,5

Table 8
Distance of two alternative based C1 criteria.

C1	E1	E2	E3	E4	E5	E6	E7
E1	0	0,767	0,93	0,93	0,767	0,446	0,986
E2	0,767	0	0,446	0,446	0	0,446	0,767
E3	0,93	0,446	0	0	0,446	0,767	0,446
E4	0,93	0,446	0	0	0,446	0,767	0,446
E5	0,767	0	0,446	0,446	0	0,446	0,767
E6	0,446	0,446	0,767	0,767	0,446	0	0,93
E7	0,986	0,767	0,446	0,446	0,767	0,93	0

Table 9
$\boldsymbol{\phi_c}$ matrix based on C1 criteria.

C1	E1	E2	E3	E4	E5	E6	E7
E1	0	0,297	0,36	0,36	0,297	0,173	0,382
E2	−0,3	0	0,173	0,173	0	−0,17	0,297
E3	−0,36	−0,17	0	0	−0,17	−0,3	0,173
E4	−0,36	−0,17	0	0	−0,17	−0,3	0,173
E5	−0,3	0	0,173	0,173	0	−0,17	0,297
E6	−0,17	0,173	0,297	0,297	0,173	0	0,36
E7	−0,38	−0,3	−0,17	−0,17	−0,3	−0,36	0

Dominance value is calculated with distance values. For this purpose, Eq. (21) is considered for the calculation. The weights in Table 7 are taken into account in this regard. Loss is taken as $\theta = 1$ for the criteria. The f_i values calculated for the C1 criterion are given in Table 9.

In this framework, ϕ_c values are calculated among the other 6 criteria. Equation (20) is used to calculate the sum of these values and the matrix δ can be generated. Then, countries are listed with the help of Eq. (22) through this calculated matrix. Final rankings are given in Table 10.

Robustness Check

For robustness check, the criteria have also been evaluated by using fuzzy DEMATEL method. Another robustness check is also performed by making analysis with triangular and trapezoidal fuzzy numbers. By considering the other alpha values in the range of (0.1)-1, the weights are calculated with DEMATEL. The summary of the results is demonstrated on Table 11.

It is also concluded that the results of trapezoidal numbers are quite different. In addition, regarding the analysis results of fuzzy DEMATEL, economic development and technological competence are found as the most essential factors that affect energy efficiency by considering triangular and Gaussian fuzzy numbers. However, the results with trapezoid numbers are different.

Moreover, the second robustness check has also been made for ranking the alternatives. The analysis results are indicated in Table 12. When the results are compared, the ranking seems to be similar. In other words, it is concluded that the ranking results in TODIM method are quite coherent for each triangular, trapezoidal and Gaussian fuzzy numbers.

At the following stage, sensitivity analysis is also applied for controlling the consistency of the criteria and the hybrid decision making approach. For this purpose, the Entropy results of the criteria are changed consecutively in the weighted decision matrix with seven cases and the ranking results are calculated for each case. This procedure is employed for triangular and trapezoidal, and Gaussian models respectively. Additionally, the TOPSIS method is also used for comparing the ranking results and illustrating the coherency of the proposed model. The ranking results of the TODIM and TOPSIS with seven cases are represented based on triangular, trapezoidal, and Gaussian approaches in Table 13.

In Table 13, the comparative ranking results are similar for each case. Thus, the sensitivity analysis results demonstrate that the proposed decision-making approach with the triangular, trapezoidal, and gaussian models are coherent and could be also employed for the extensive applications of real-world problems.

5. Discussion and conclusions

In this study, the energy efficiency of E7 countries has been evaluated. In this context, firstly, a literature review has been made on the subject, and 7 different criteria that could be used in measuring energy efficiency are determined. Later, these criteria are weighted by considering Gaussian fuzzy Entropy methodology. After that, E7 countries are ranked regarding the performance of energy efficiency with Gaussian fuzzy TODIM approach. Additionally, the criteria have also been evaluated by using DEMATEL for robustness check. Moreover, the alternatives are also ranked by using TOPSIS to evaluate the coherency of the analysis results. Furthermore, the calculations are also made with triangular and trapezoidal fuzzy numbers to control the reliability of the proposed model. Finally, with the help of making sensitivity analysis by considering 7 different conditions, the validity of the proposed model can be measured. With respect to the evaluation made by entropy method, the analysis results with triangular and Gaussian fuzzy numbers are quite coherent. However, it is also identified that the weights calculated by trapezoidal numbers are different. On the other side, the analysis results of DEMATEL and TOPSIS are almost the same for three different number types. The findings demonstrate that economic development and technological competency are the main factors that increase energy efficiency. It is also stated that Russia and Brazil are the most successful countries in energy efficiency whereas India and Turkey are in the last places.

Furthermore, the results indicate that economic development of the countries is the most important factor to increase energy efficiency. It is obvious that the countries with economic stability are more successful in the efficient use of energy. The main reason is that countries with strong economies show greater importance to research and development. In this way, these countries possess the necessary knowledge for the efficient use of energy. Moreover, the legal infrastructure in these countries contributes to more efficient use of energy. This situation was also discussed in the literature by many different researchers. For instance, Balitskiy et al. (2016) aimed to analyze the relationship between economic development and energy efficiency in European Union countries. Regression analysis was taken into account in this study. They defined economic growth as an important indicator in energy efficiency. Pan et al. (2019) also focused on this relationship for different country groups and argued that there is a direct relationship between economic growth and energy efficiency. Similar to these studies, Razzaq et al. (2021) and Usman et al. (2021) tried to identify the significant points that affect energy efficiency. They highlighted that the countries, which have economic power, can make research and development effectively. This situation has a direct contribution to achieve energy efficiency.

Additionally, it is also defined that technological developments play a very key role with respect to the efficiency of energy usage. With the help of following and applying new applications

Table 10
δ matrix and ranking.

Countries	E1	E2	E3	E4	E5	E6	E7	Sum	ξ	Ranking
E1	0	0,943	1,544	0,424	0,597	−0,17	1,736	5,071	0,877	2
E2	−0,94	0	0,605	−0,41	−0,39	−1,16	1,011	−1,29	0,463	5
E3	−1,54	−0,61	0	−1,38	−1,17	−1,87	0,444	−6,13	0,148	6
E4	−0,42	0,408	1,381	0	0,11	−0,81	1,465	2,127	0,685	3
E5	−0,6	0,394	1,167	−0,11	0	−0,88	1,673	1,651	0,654	4
E6	0,172	1,159	1,874	0,813	0,876	0	2,061	6,956	1,000	1
E7	−1,74	−1,01	−0,44	−1,47	−1,67	−2,06	0	−8,39	0,000	7

Table 11
Comparison of Entropy and DEMATEL results.

Criteria	Entropy			DEMATEL		
	Triangular	Gaussian	Trapezoid	Triangular	Gaussian	Trapezoid
Technological Competence (C1)	0.150124066	0.1501240661	0.1381918	0.154918084	0.15799745	0.15601803
Government Support (C2)	0.134761847	0.134761847	0.1450451	0.132637852	0.13191444	0.133686111
People's Consciousness (C3)	0.139476786	0.139476786	0.1509185	0.126574457	0.12431734	0.12358044
Renewable Energy Usage (C4)	0.141656456	0.141656456	0.1495709	0.137310861	0.13821391	0.144895455
Economic Development (C5)	0.150729964	0.150729964	0.1323524	0.154272952	0.15410898	0.147957948
Legal Sufficiency (C6)	0.136111461	0.136111461	0.1380216	0.148369062	0.14949375	0.150574471
Qualified Employee (C7)	0.147139421	0.147139421	0.1458994	0.145916732	0.14395409	0.143287546

in energy, it will be possible to increase the saving in energy use. The important point in this process is the necessity to closely follow the technological developments in this field. Therefore, it is important for countries to master current developments, such as renewable energy, energy storage, and carbon capture in order to increase their energy efficiency. Many different studies in the literature also reached similar conclusions. For example, Cantore et al. (2016) aimed to define the ways to improve energy efficiency in 29 different developing countries. It is identified that the technological infrastructure of the country should be sufficient to use the energy more efficiently. Zhang et al. (2017) also developed the iron and steel industry in China by using regression analysis. It is identified that countries with advanced technology use energy more efficiently. Also, Chen et al. (2021), Li et al. (2021b) and Konieczna et al. (2021) evaluated the influencing factors of the energy efficiency. They stated that technological innovation has a direct impact on the energy efficiency.

In the literature, there are also some other studies which underlined the significance of different factors to increase energy efficiency. For example, Alam et al. (2019) aimed to increase the energy efficiency in public buildings. They reached a conclusion that qualified personnel play the most significant role to achieve this objective. Büth et al. (2018), Hansen et al. (2020) and Hassan et al. (2017) also highlighted the importance of the qualification of the employee for the improvement of the energy efficiency. On the other side, Safarzadeh and Rasti-Barzoki (2019) made a study to understand the key issues to increase energy efficiency. They identified that governments should give necessary supports to achieve this objective. Moreover, Carbonara and Pellegrino (2018b) and Figus et al. (2017) also underlined the importance of this situation. They mainly claimed that governments should give some subsidies for the energy savings so that energy efficiency can be provided.

The biggest limitation of this study is that there has not been a practical application within the sector regarding the results obtained. The results obtained in this study are only indicative. In other words, the practical appropriateness of these considerations has not been tested on a company. Therefore, it is thought that a practical applied study on energy efficiency will be very beneficial in new studies. Another important limitation is that only E7 countries are taken into consideration during the analysis process. These results may differ for other country groups. In this context, it is thought that a new analysis, especially for energy importing countries, will contribute to the literature. On the other hand, the use of a different method in the analysis will increase the methodological originality of the study. Energy is a vital issue for

Table 12
Comparative TODIM results.

	Triangular		Trapezoid		Gaussian	
	ξ	Ranking	ξ	Ranking	ξ	Ranking
E1	0,921	2	0,921	2	0,877	2
E2	0,534	5	0,537	5	0,462	5
E3	0,125	6	0,134	6	0,148	6
E4	0,707	4	0,709	4	0,685	3
E5	0,763	3	0,758	3	0,654	4
E6	1	1	1	1	1	1
E7	0	7	0	7	0	7

Table 13
Sensitivity analysis results for the proposed TODIM and TOPSIS models.

	Case 1						Case 2						Case 3					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
E1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
E2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
E3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
E4	4	4	3	3	4	3	4	4	3	3	4	3	4	4	3	4	4	4
E5	3	3	4	4	3	4	3	3	4	4	3	4	3	3	4	3	3	3
E6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
E7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	Case 4						Case 5						Case 6					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
E1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
E2	5	6	5	5	6	5	5	6	5	5	6	5	5	5	5	5	5	5
E3	6	5	6	6	5	6	6	5	6	6	5	6	6	6	6	6	6	6
E4	4	4	3	4	4	3	4	4	3	4	4	3	4	4	3	3	4	3
E5	3	3	4	3	3	4	3	3	4	3	3	4	3	3	4	4	3	4
E6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
E7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	Case 7																	
	M1	M2	M3	M4	M5	M6												
E1	2	2	2	2	2	2												
E2	5	5	5	5	5	5												
E3	6	6	6	6	6	6												
E4	4	4	3	3	4	3												
E5	3	3	4	4	3	4												
E6	1	1	1	1	1	1												
E7	7	7	7	7	7	7												

*M1: Triangular TODIM, M2: Trapezoidal TODIM, M3: Gaussian TODIM, M4: Triangular TOPSIS, M5: Trapezoidal TOPSIS, M6: Gaussian TOPSIS the whole world; therefore, it is concluded that it will be useful to address issues, such as risk management, cost analysis, and new energy methods in the energy sector in the future studies.

CRediT authorship contribution statement

Wei Liu: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Hasan Dinçer:** Visualization, Investigation, Methodology, Conceptualization. **Serkan Eti:** Supervision, Software, Validation, Methodology, Conceptualization. **Serhat Yüksel:** Investigation, Methodology, Writing - review & editing.

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.

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