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Research paper

Analysis of renewable-friendly smart grid technologies for the distributed energy investment projects using a hybrid picture fuzzy rough decision-making approach

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ABSTRACT

Smart grid systems help increase RWJ projects (RWJ) so that environmentally friendly energy production can be generated. However, efficient technologies should be implemented to ensure the sustainability of smart grid systems. This study aims to evaluate renewable-friendly smart grid technologies regarding distributed energy investment projects by using a hybrid picture fuzzy rough decision-making approach. Firstly, selected criteria are weighted using the multi stepwise weight assessment ratio analysis (M-SWARA) method based on picture fuzzy rough sets (PFRSs). Subsequently, different renewable-friendly smart grid technologies are ranked with the complex proportional assessment (COPRAS) technique by using PFRSs. It is determined that research and development play the most critical role with respect to the renewable-friendly smart grid technologies for distributed energy investment projects. On the other side, cost is another essential factor for this issue. It is also identified that direct current links are the most important renewable-friendly smart grid technology alternative. Priorities should be given to the development of research and development studies on renewable energies to increase the efficiency of smart grid systems. In this context, private sector companies have a very important role. Similarly, incentives provided by governments to RWJ research and development studies should be increased. Within the scope of these studies, new technologies for RWJ types should be emphasized. In this context, new technologies for all RWJ alternatives should be followed comprehensively. Increasing research and development for such investments will also make smart grid systems more successful.

1. Introduction

Global warming causes long-term droughts (Tebaldi et al., 2021). There will potentially not be enough water in the soil to meet the needs of plant life, leading to decreasing numbers of agricultural products. In addition, glaciers are melting, causing sea and ocean levels to rise (Alfonso et al., 2021). Melting glaciers cause floods and extreme heat waves. There may be an increase in hunger and water crise, especially in developing countries. As a result, it is necessary to determine the root causes of the global warming problem and take the necessary precautions (Guan et al., 2021). Depending on the use of fossil fuels, the amount of greenhouse gases can increase significantly. This situation raises the problem of carbon emission (Mutezo and Mulopo, 2021). Fossil fuels for energy production are preferred by many countries around the world. This is because the cost of using fossil fuels is currently lower than other types of energy. This attracts the attention of investors (Adebayo et al., 2021). Furthermore, it is possible to predict the amount of energy that will be produced by using fossil fuels. This complex of factors increases the use of fossil fuels, causing the problem of global warming to deepen (Bhuiyan et al., 2022).

It is necessary to focus on alternative energy sources instead of fossil fuels. Therefore, the importance of RWJ sources, which are called green energy sources, has been emphasized due to the global warming problem (Dong et al., 2021). In this process, renewable and inexhaustible energy sources such as the sun are

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taken into consideration. Harmful gases are not produced because of using these sources (Yuping et al., 2021). In other words, the amount of carbon emissions can be significantly reduced with RWJ. Due to these advantages, many countries are trying to develop RWJ sources (Zheng et al., 2021). On the other hand, RWJ types also have some disadvantages. These energy sources are affected by different climatic conditions. As a result, the amount of energy obtained may vary during the day. This causes the amount of produced energy to be unstable (Levenda et al., 2021). In this process, excess energy can be stored to provide stability. This increases the costs of these types of energy (Corizzo et al., 2021). Therefore, it is necessary to reduce the cost of these projects through technological developments and innovation. This will contribute to the increase of RWJ projects (Dinçer et al., 2022).

The idea is that research and development studies on RWJ technologies should be increased to reduce costs. In this context, it is important to follow new developments in these technologies. In addition, new technologies developed should be integrated into projects immediately (Wei et al., 2021). This will help increase the projects' efficiency. On the other hand, distributed energy investment projects also contribute to increasing the efficiency of these investments (Kozlova and Overland, 2021). These projects aim at energy production at the point of consumption. Since electricity is produced on-site, the user is not affected by the problems that occur in energy transmission. This helps reduce energy production and consumption costs (Azam et al., 2021).

Smart grid systems help improve RWJ projects so that environmentally friendly energy production can be developed. Despite this issue, efficient technologies should be implemented for the sustainability of smart grid systems. Otherwise, it becomes very difficult to provide sustainability of these projects. It is aimed to examine renewable-friendly smart grid technologies regarding the distributed energy investment projects. For this purpose, a hybrid novel picture fuzzy rough decision-making approach is presented. At the first stage, the weights of the selected criteria are calculated using the M-SWARA method based on PFRSs. Secondly, different renewable-friendly smart grid technologies are ranked with the COPRAS technique by considering PFRSs.

The main important novelty of this study is providing significant solutions to improve renewable-friendly smart grid technologies for the distributed energy investment projects with a new hybrid picture fuzzy rough decision-making approach. The novelty also includes three points: private sector companies have a very important role in green investments, cost efficiency is the main issue for the development of the renewable-friendly smart grid technologies, synchrophasors and flexible alternating current transmission systems are on the last ranks.

The obtained results allow to produce the necessary strategies for the development of distributed energy investment projects. It is thought that these strategies will be beneficial to both investors and researchers. Researchers can make necessary improvements by considering the model produced in this study. Furthermore, investors and policy makers can take effective and correct decisions to develop these projects by considering the results of this study.

The decision-making model produced in this study also has some advantages compared to the decision-making methods previously developed in the literature. Firstly, some improvements were made on the SWARA method, and the M-SWARA technique was developed. With the use of this model, it is possible to manage uncertainties in the decision-making process more efficiently (Sivageerthi et al., 2021; Vrtagić et al., 2021). This gives the proposed model an advantage compared to other studies using the SWARA technique (Ulutaş et al., 2021; Thakkar, 2021). In addition, ambiguous nature of subjective judgments can be reflected more appropriately by considering PFRSs in the analysis process (Wei, 2016; Li et al., 2022). Moreover, expert opinions can be evaluated more accurately in comparison with other techniques used to weight the items (Son, 2017; Thao, 2020). On the other hand, the main benefit of COPRAS over other approaches is to express utility degrees (Krishankumar et al., 2021; Dorfeshan and Mousavi, 2019; Goswami et al., 2021). Finally, in all the stages of the proposed model, the calculations are made with decision making techniques (SWARA and COPRAS). That is to say, the weights of the factors are not defined by the authors. Hence, by creating a hybrid methodology, more objective evaluations can be performed (Haiyun et al., 2021; Yuan et al., 2021).

The renewable-friendly smart grid technologies are also reviewed for the distributed energy investment projects in different ways. Sustainable development can become a way to solve problems in the energy sector with the addition of the already existing criterion of economic efficiency, ESG criteria. The BRICS countries are integrating these criteria into national development strategies, which gives new solutions to energy efficiency issues, which seems to be a priority (Moiseev et al., 2020; Mutalimov et al., 2021; Kranina, 2021; Bushukina, 2021; Matveeva, 2021).

Literature is examined in the second section. Methodological information is presented in the following section. Next, analysis results are provided. The discussion is featured in the final part.

2. Literature review

For the improvement of the renewable-friendly smart grid technologies, some scholars focused on research and development activities. The existing electrical infrastructure in smart grid systems is blended with today's modern information technologies (Rathor and Saxena, 2020). In this way, it aims to meet the energy needs of countries to a significant extent. Smart grid projects involve complex processes (Butt et al., 2020). Therefore, for these projects to be successful, the design must be created efficiently (Steinbrink et al., 2018). In order to achieve this goal, importance should be given to research and development studies (Marten et al., 2018). As a result, it will be possible for the clean energy types, network communications and storage centres in the smart grid system to operate more efficiently (Montoya et al., 2020). This will contribute to the operations of the projects. Ganguly et al. (2019) evaluated the security measures in smart grid systems and defined that research and development activities should be prioritized in this respect. Al-Badi et al. (2020) made an evaluation regarding the smart grid technologies in Oman. They highlighted the significance of new research's goal to increase the efficiency of these projects. Uslar et al. (2019) examined the issues to increase the performance of the smart grid systems in the EU and claimed that research and development plays a key role in this situation.

Furthermore, smart grid energy projects significantly help to increase the use of clean energy (Abdalla et al., 2020). However, for these projects to be sustainable, they should be preferred by investors. In this context, a detailed market analysis should be conducted regarding this issue (Velte and Aguirrebeitia, 2019). As a result, the overall volume of demand for smart grid projects should be identified. Subsequently, some commercial activities should be emphasized to increase the demand for these projects (Adnan et al., 2018). In this context, information regarding the advantages of these projects should be communicated to investors (Aldieri and Vinci, 2021). In this way, it will be possible to boost the demand for these projects at a large scale. Huang (2019) made a study about the RWJ-based smart grid systems. They stated that for the aim of increasing demand, companies should prioritize commercial activities. Bhatti and Danilovic (2018) aimed to identify leading indicators of smart grid systems. It is concluded that commercialization is necessary to reach this objective. Gharehpetian et al. (2018) evaluated Iranian smart grid projects and identified that for the creation of large-scale demand, a comprehensive commercialization policy should be enacted.

Cost efficiency is another critical issue for the development of renewable-friendly smart grid technologies. One of the biggest aims of the creation of smart grid projects is to create a common network and to minimize the high-cost problem of RWJ investments (Zhang et al., 2019). In this framework, excess energy can be stored or sold to other parties (Asgher et al., 2018). Moreover, it is aimed to increase the efficiency of the projects by sharing the costs of the storage process by the parties of the network (Ferro et al., 2018). Therefore, the cost analysis should be done correctly in the process of creating smart grid projects (Castello et al., 2018). Otherwise, these projects will not be attractive to investors, and will not contribute to the increase of clean energy use. Shuja et al. (2019) studied smart grid systems and determined that a detailed cost–benefit analysis should be conducted to increase the performance of these projects. Artale et al. (2018) also concluded that cost analysis should be made effectively for the success of smart grid systems. Alaqeel and Suryanarayanan (2019) evaluated Saudi Arabian smart grid technologies and identified that a comprehensive cost–benefit analysis should be conducted.

Customer satisfaction also plays a crucial role regarding the sustainability of the renewable-friendly smart grid technologies according to some studies. Energy production and distribution processes of this system can be accompanied by technical issues (Laakkonen and Kivivirta, 2021). In this context, companies should create an efficient system that can solve customers' technical problems quickly (Rahman et al., 2020). This can yield the result of increasing customer satisfaction (Li et al., 2019). Otherwise, these projects cannot be preferable, the sustainability of these projects would be in jeopardy (Ghaffari and Afsharchi, 2021). Caputo et al. (2018) aimed to identify the critical factors of the performance improvement regarding smart grid projects. They determined that an effective system should be constructed to solve the customers' technical problems quickly. Lamb and Agarwal (2020) also identified that with the aim of improving smart grid technologies, customer needs should be met at full capacity. Deilami and Muyeen (2020) also claimed that customer satisfaction plays a critical role in ensuring sustainability of the renewable-friendly smart grid technologies.

According to the results of the literature evaluations, some critical points can be reached. Firstly, smart grid technologies play a crucial role for the improvements of the clean energy productions. However, these projects have some difficulties, such as high costs and technical necessity. Therefore, efficient technological support should be implemented for the sustainability of smart grid systems. Within this framework, a new analysis is required to determine key issues for designing smart grid systems. This study aims to examine renewable-friendly smart grid technologies regarding distributed energy investment projects. In this context, a hybrid novel picture fuzzy rough decision-making approach is presented.

3. Methodology

Picture fuzzy rough sets and proposed model are explained in this part.

3.1. Picture fuzzy rough sets

The methods of this paper are based on previous fundamental papers which already use combinations of hybrid picture fuzzy rough decision-making approaches (Abdel-Basset et al., 2021; Huang et al., 2022). Cuong (2014) generated picture fuzzy sets (PFSs) for the purpose of making more efficient evaluations to solve decision-making problems. Within this context, different membership degrees are used. Eq. (1) provides information about the traditional fuzzy sets. In this process, X represents the universe and μ_A refers to the membership degree.

$$A = \{\langle x, \mu_A(x)\rangle \,|x \in X\} \tag{1}$$

Intuitionistic fuzzy sets include both membership and non-membership (υ_A) degrees as in Eq. (2) (Atanassov, 1999).

$$A = \{\langle x, \mu_A(x), \upsilon_A(x)\rangle \,|x \in X\} \tag{2}$$

For these sets, the condition of $0 \leq \mu_A(x) + \upsilon_A(x) \leq 1$ should be met. Additional function parameters are considered in PFSs as in Eq. (3). In this framework, n_A and π_A indicate neutral and refusal degrees with the condition of $\mu_A(x) + n_A(x) + \upsilon_A(x) + \pi_A(x) = 1$.

$$A = \{\langle x, \mu_A(x), n_A(x), \upsilon_A(x), \pi_A(x)\rangle \,|x \in X\} \tag{3}$$

In PFSs, μ_A, n_A, υ_A and π_A demonstrate the opinions of "yes", "abstain", "no" and "ignoring". Eqs. (4)–(8) represent the details of the calculation (Wei, 2016).

$$A \subseteq B \text{ if } \mu_A(x) \leq \mu_B(x) \text{ and } n_A(x) \leq n_B(x) \text{ and } \upsilon_A(x) \geq \upsilon_B(x), \ \forall x \in X \tag{4}$$

$$A = B \text{ if } A \subseteq B \text{ and } B \subseteq A \tag{5}$$

$$A \cup B = \{(x, max(\mu_A(x), \mu_B(x)), min(n_A(x), n_B(x)), min(\upsilon_A(x), \upsilon_B(x))) \,|x \in X\} \tag{6}$$

$$A \cap B = \{(x, min(\mu_A(x), \mu_B(x)), min(n_A(x), n_B(x)), max(\upsilon_A(x), \upsilon_B(x))) \,|x \in X\} \tag{7}$$

$$coA = \overline{A} = \{(x, \upsilon_A(x), n_A(x), \mu_A(x)) \,|x \in X\} \tag{8}$$

Zhai et al. (2008) introduced rough numbers to provide objectivity in the evaluations. For this purpose, lower and upper limits ($\underline{Apr}(C_i)$, $\overline{Apr}(C_i)$) and the boundary region ($Bnd(C_i)$) are considered in Eqs. (9)–(11). In this process, Y represents the arbitrary object and R gives information about the sets.

$$\underline{Apr}(C_i) = \cup\{Y \in X/R(Y) \leq C_i\} \tag{9}$$

$$\overline{Apr}(C_i) = \cup\{Y \in X/R(Y) \geq C_i\} \tag{10}$$

$$Bnd(C_i) = \cup\{Y \in X/R(Y) \neq C_i\} \tag{11}$$

On the other side, Eqs. (12)–(14) are used to define the rough number ($RN(C_i)$), lower ($\underline{Lim}(C_i)$) and upper ($\overline{Lim}(C_i)$) limits.

$$\underline{Lim}(C_i) = \sqrt[N_L]{\prod_{i=1}^{N_L} Y \in \underline{Apr}(C_i)} \tag{12}$$

$$\overline{Lim}(C_i) = \sqrt[N_U]{\prod_{i=1}^{N_U} Y \in \overline{Apr}(C_i)} \tag{13}$$

$$RN(C_i) = \left\lceil \underline{Lim}(C_i), \overline{Lim}(C_i) \right\rfloor \tag{14}$$

In this study, PFSs are integrated with rough numbers. Eqs. (15)–(22) explain the details of picture fuzzy rough sets (PFRSs).

$$\underline{Apr}\left(C_{i\mu_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{i\mu_A}\right\} \tag{15}$$

$$\underline{Apr}\left(C_{in_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{in_A}\right\} \tag{16}$$

$$\underline{Apr}\left(C_{i\upsilon_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{i\upsilon_A}\right\} \tag{17}$$

$$\underline{Apr}\left(C_{i\pi_A}\right) = \cup \left\{ Y \in X/\tilde{R}(Y) \le C_{i\pi_A} \right\} \tag{18}$$

$$\overline{Apr}\left(C_{i\mu_A}\right) = \cup \left\{ Y \in X/\tilde{R}(Y) \le C_{i\mu_A} \right\} \tag{19}$$

$$\overline{Apr}\left(C_{in_A}\right) = \cup \left\{ Y \in X/\tilde{R}(Y) \le C_{in_A} \right\} \tag{20}$$

$$\overline{Apr}\left(C_{iv_A}\right) = \cup \left\{ Y \in X/\tilde{R}(Y) \le C_{iv_A} \right\} \tag{21}$$

$$\overline{Apr}\left(C_{i\pi_A}\right) = \cup \left\{ Y \in X/\tilde{R}(Y) \le C_{i\pi_A} \right\} \tag{22}$$

Eqs. (23)–(30) are considered to define the limits in these sets.

$$\underline{Lim}\left(C_{i\mu_A}\right) = \frac{1}{N_{L\mu_A}} \sum_{i=1}^{N_{L\mu_A}} Y \in \underline{Apr}\left(C_{i\mu_A}\right) \tag{23}$$

$$\underline{Lim}\left(C_{in_A}\right) = \frac{1}{N_{Ln_A}} \sum_{i=1}^{N_{Ln_A}} Y \in \underline{Apr}\left(C_{in_A}\right) \tag{24}$$

$$\underline{Lim}\left(C_{iv_A}\right) = \frac{1}{N_{Lv_A}} \sum_{i=1}^{N_{Lv_A}} Y \in \underline{Apr}\left(C_{iv_A}\right) \tag{25}$$

$$\underline{Lim}\left(C_{i\pi_A}\right) = \frac{1}{N_{L\pi_A}} \sum_{i=1}^{N_{L\pi_A}} Y \in \underline{Apr}\left(C_{i\pi_A}\right) \tag{26}$$

$$\overline{Lim}\left(C_{i\mu_A}\right) = \frac{1}{N_{U\mu_A}} \sum_{i=1}^{N_{U\mu_A}} Y \in \overline{Apr}\left(C_{i\mu_A}\right) \tag{27}$$

$$\overline{Lim}\left(C_{in_A}\right) = \frac{1}{N_{Un_A}} \sum_{i=1}^{N_{Un_A}} Y \in \overline{Apr}\left(C_{in_A}\right) \tag{28}$$

$$\overline{Lim}\left(C_{iv_A}\right) = \frac{1}{N_{Uv_A}} \sum_{i=1}^{N_{Uv_A}} Y \in \overline{Apr}\left(C_{iv_A}\right) \tag{29}$$

$$\overline{Lim}\left(C_{i\pi_A}\right) = \frac{1}{N_{U\pi_A}} \sum_{i=1}^{N_{U\pi_A}} Y \in \overline{Apr}\left(C_{i\pi_A}\right) \tag{30}$$

Picture fuzzy rough number of $\widetilde{C}_i$ $PFRN\left(\widetilde{C}_i\right)$ is calculated as in Eq. (31).

$$PFRN\left(\widetilde{C}_i\right) = \left(\left\lceil \underline{Lim}\left(C_{i\mu_A}\right), \overline{Lim}\left(C_{i\mu_A}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{in_A}\right), \overline{Lim}\left(C_{in_A}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{iv_A}\right), \overline{Lim}\left(C_{iv_A}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{i\pi_A}\right), \overline{Lim}\left(C_{i\pi_A}\right)\right\rfloor\right) \tag{31}$$

3.2. Proposed decision-making method based on PFRSs

In this study, a model is created with M-SWARA and COPRAS based on PFRSs. Firstly, a criteria list is generated with the help of literature evaluations. Secondly, evaluations are collected from experts. The picture fuzzy relation matrix is developed in the third step as in Eq. (32) (Bo and Zhang, 2017).

$$\tilde{Z}_k = \begin{bmatrix} 0 & \widetilde{z}_{12} & \cdots & \cdots & \widetilde{z}_{1n} \\ \widetilde{z}_{21} & 0 & \cdots & \cdots & \widetilde{z}_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \widetilde{z}_{n1} & \widetilde{z}_{n2} & \cdots & \cdots & 0 \end{bmatrix} \tag{32}$$

Eq. (33) is considered to generate PFR numbers.

$$PFRN\left(\widetilde{C}_{ij}\right) = \left(\left\lceil \underline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right), \overline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right), \overline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{ijv_{\tilde{z}_{ij}}}\right), \overline{Lim}\left(C_{ijv_{\tilde{z}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(C_{ij\pi_{\tilde{z}_{ij}}}\right), \overline{Lim}\left(C_{ij\pi_{\tilde{z}_{ij}}}\right)\right\rfloor\right) \tag{33}$$

Fifth, comparative importance rate $(\tilde{s}_j)$, coefficient value $(\tilde{k}_j)$, recalculated weight $(\tilde{q}_j)$, and weights $(\tilde{w}_j)$ are computed by Eqs. (34)–(36).

$$\tilde{k}_j = \begin{cases} 1 & j = 1 \\ \tilde{s}_j + 1 & j > 1 \end{cases} \tag{34}$$

$$\tilde{q}_j = \begin{cases} 1 & j = 1 \\ \frac{\tilde{k}_{j-1}}{\tilde{k}_j} & j > 1 \end{cases} \tag{35}$$

$$\tilde{w}_j = \frac{q_j}{\sum_{k=1}^{n} q_k} \tag{36}$$

Eqs. (37)–(39) are used to implement defuzzification (Zeng et al., 2019).

$$w_{jmin} = \underline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right) + \frac{\underline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2} + \frac{\left(1 + \underline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right) + \frac{\underline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2} - \underline{Lim}\left(C_{ijv_{\tilde{z}_{ij}}}\right) + \frac{\underline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2}\right)}{2} \times \underline{Lim}\left(C_{ij\pi_{\tilde{z}_{ij}}}\right) \tag{37}$$

$$w_{jmax} = \overline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right) + \frac{\overline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2} + \frac{\left(1 + \overline{Lim}\left(C_{ij\mu_{\tilde{z}_{ij}}}\right) + \frac{\overline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2} - \overline{Lim}\left(C_{ijv_{\tilde{z}_{ij}}}\right) + \frac{\overline{Lim}\left(C_{ijn_{\tilde{z}_{ij}}}\right)}{2}\right)}{2} \times \overline{Lim}\left(C_{ij\pi_{\tilde{z}_{ij}}}\right) \tag{38}$$

$$w_j = \frac{\left(w_{jmin} + w_{jmax}\right)}{2} \tag{39}$$

The stable matrix is created by transposing and limiting the matrix to the power of 2k+1. In the second part of the model, alternatives are ranked with COPRAS based on PFRSs. Eq. (40) explains the decision matrix (Krishankumar et al., 2021).

$$\tilde{X}_{ij} = \begin{matrix} & C_1 & C_2 & C_3 & \dots & C_n \\ A_1 & x_{11} & x_{12} & x_{13} & \cdots & x_{1n} \\ A_2 & x_{21} & x_{22} & x_{23} & \cdots & x_{2n} \\ A_3 & x_{31} & x_{32} & x_{33} & \cdots & x_{3n} \\ \vdots & \vdots & \vdots & \ddots & \cdots & \vdots \\ A_m & x_{m1} & x_{m2} & x_{m3} & \cdots & x_{mn} \end{matrix} \tag{40}$$

PFRSs are identified by Eq. (41).

$$PFRN\left(\tilde{X}_{ij}\right) = \left(\left\lceil \underline{Lim}\left(\tilde{X}_{ij\mu_{\tilde{x}_{ij}}}\right), \overline{Lim}\left(\tilde{X}_{ij\mu_{\tilde{x}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(\tilde{X}_{ijn_{\tilde{x}_{ij}}}\right), \overline{Lim}\left(\tilde{X}_{ijn_{\tilde{x}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(\tilde{X}_{ijv_{\tilde{x}_{ij}}}\right), \overline{Lim}\left(\tilde{X}_{ijv_{\tilde{x}_{ij}}}\right)\right\rfloor, \left\lceil \underline{Lim}\left(\tilde{X}_{ij\pi_{\tilde{x}_{ij}}}\right), \overline{Lim}\left(\tilde{X}_{ij\pi_{\tilde{x}_{ij}}}\right)\right\rfloor\right) \tag{41}$$

Normalized values are calculated by Eq. (42).

$$\tilde{r}_{ij} = \frac{\underline{Lim}\left(\tilde{X}_{ij\mu_{\tilde{x}_{ij}}}\right)}{max\tilde{X}_i}, \ldots, \frac{\overline{Lim}\left(\tilde{X}_{ij\pi_{\tilde{x}_{ij}}}\right)}{max\tilde{X}_i} \tag{42}$$

Eq. (43) is used to define weighted matrix.

$$\tilde{v}_{ij} = w_j \times \underline{Lim}\left(\tilde{r}_{ij\mu_{\tilde{x}_{ij}}}\right), \ldots, w_j \times \overline{Lim}\left(\tilde{r}_{ij\pi_{\tilde{x}_{ij}}}\right) \tag{43}$$

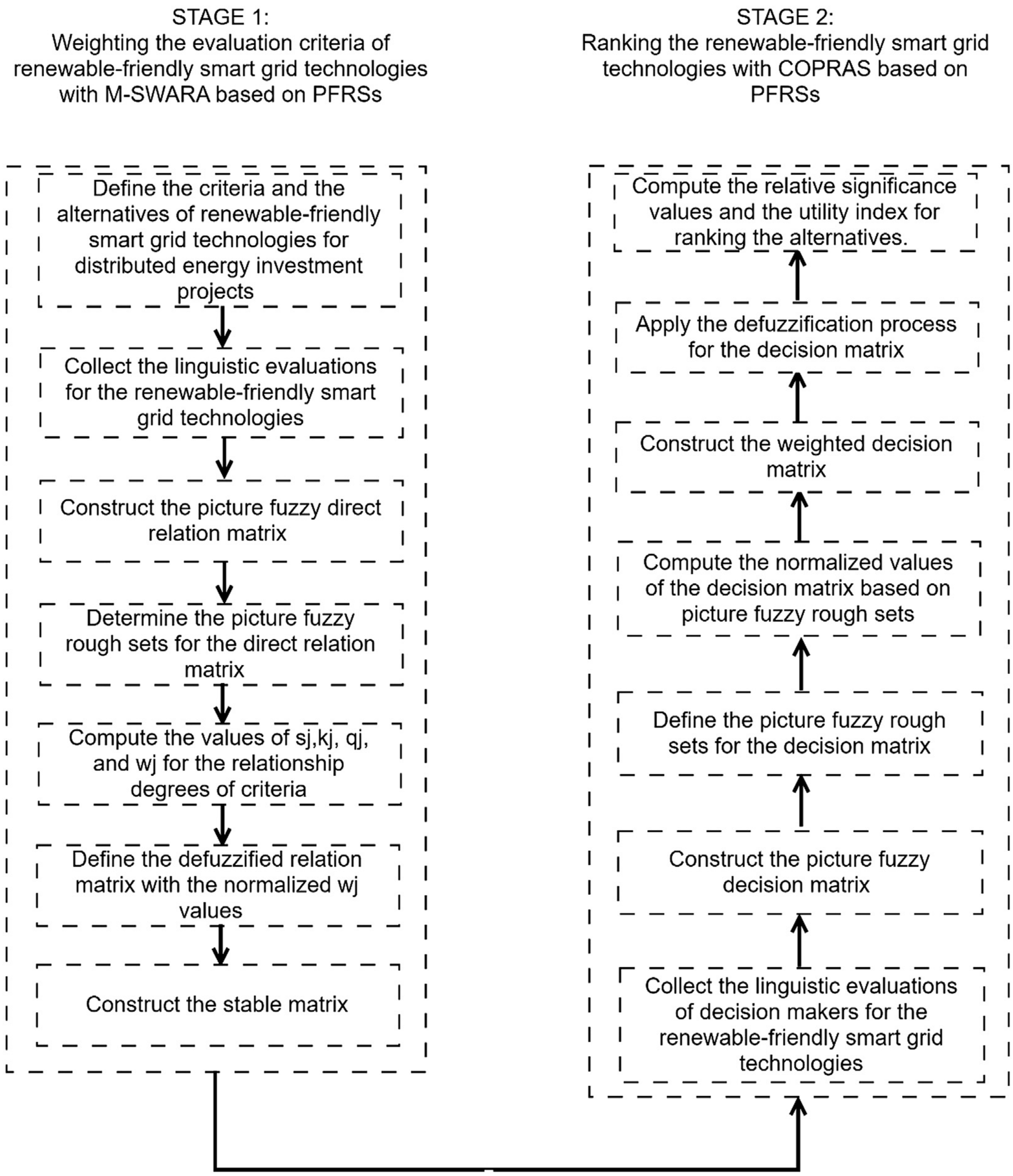

Fig. 1. The flowchart of hybrid model.

Eq. (44) is considered to compute the relative significance value by using benefit and non-benefit criteria (v_{ij+}, v_{ij-}) (Goswami et al., 2021).

$$Q_i = \sum_{j=1}^{t} v_{ijbenefit} + \frac{R_{min} \sum_{i=1}^{m} \sum_{j=t+1}^{n} v_{ijnon-benefit}}{\sum_{j=t+1}^{n} v_{ijnon-benefit} \sum_{i=1}^{m} \frac{R_{min}}{\sum_{j=t+1}^{n} v_{ijnon-benefit}}} \quad (44)$$

Utility index is calculated as in Eq. (45) (Dorfeshan and Mousavi, 2019).

$$U_i = \frac{Q_i}{Q_{max}} \times 100\% \quad (45)$$

4. Analysis

A new model is generated for the evaluation of renewable-friendly smart grid technologies regarding the distributed energy investment projects by using a hybrid picture fuzzy rough decision-making approach. Fig. 1 explains the process of this model.

Stage 1: Weighting the evaluation criteria of renewable-friendly smart grid technologies with M-SWARA based on PFRSs.

Step 1: Define the criteria and the alternatives of renewable-friendly smart grid technologies for distributed energy investment projects

Step 2: Collect the linguistic evaluations for the renewable-friendly smart grid technologies

Step 3: Construct the picture fuzzy direct relation matrix

Step 4: Determine the picture fuzzy rough sets for the direct relation matrix.

Step 5: Compute the values of $\tilde{s}_j$, $\tilde{k}_j$, $\tilde{q}_j$, and $\tilde{w}_j$ for the relationship degrees of criteria

Step 6: Define the defuzzified relation matrix with normalized wj values

Step 7: Construct the stable matrix

Stage 2: Ranking the renewable-friendly smart grid technologies with COPRAS based on PFRSs.

Step 1: Collect the linguistic evaluations of decision makers for the renewable-friendly smart grid technologies

Step 2: Construct the picture fuzzy decision matrix

Table 1
Selected criteria of renewable-friendly smart grid technologies for distributed energy investment projects.

Criteria	References
Research and Development (criterion 1)	Qiu et al. (2019)
Commercialization (criterion 2)	Adnan et al. (2018)
Cost (criterion 3)	Alaqeel and Suryanarayanan (2019)
Operational issues (criterion 4)	Abdalla et al. (2020)
Functionality (criterion 5)	Gharehpetian et al. (2018)

Table 2
Alternatives of smart grid technologies for distributed energy investment projects.

Criteria	References
Bulk Storage (Alternative 1)	Arroyo et al. (2020)
Direct Current Links (Alternative 2)	Niewiadomski and Baczynska (2018)
Flexible Alternating Current Transmission Systems (Alternative 3)	Naderi et al. (2019)
Dynamic Line Ratings (Alternative 4)	Viafora et al. (2020)
Synchrophasors (Alternative 5)	Wang et al. (2020)

Step 3: Define the picture fuzzy rough sets for the decision matrix.

Step 4: Compute the normalized values of the decision matrix based on picture fuzzy rough sets.

Step 5: Construct the weighted decision matrix.

Step 6: Apply the defuzzification process for the decision matrix.

Step 7: Compute the relative significance values and the utility index for ranking the alternatives.

At first, criteria are selected based on literature examination with respect to the renewable-friendly smart grid technologies for distributed energy investment projects. Table 1 indicates the details of these items.

Commercialization (criterion 2) illustrates the frequency of the commercial and common usage in the market. On the other hand, research and development (criterion 1) defines the technological development and the maturity level of the smart grid technology. Moreover, cost (criterion 3) determines the paid amount of the initial construction and upgrades for the operational efficiency. Operational issues (criterion 4) present the potential of the technical problems in the energy production and distribution process. Finally, functionality (criterion 5) provides the sufficient transmission, connection, and monitoring of the technologies. After that, different alternatives are set based on the renewable-friendly smart grid technologies as in Table 2.

In this context, bulk storage (BS) means storage of large amount of energy with the aim of using it for a long time. Direct Current Links (DC) allows to transfer power between transmission systems so that it improves the stability and economy of each grid. Flexible alternating current transmission systems (FACTS) consist of equipment for alternating current transmission of electrical energy for the purpose of improving power transfer capabilities. Dynamic line ratings (DLR) constantly take into consideration the varying line grade of a transmission line with the aim of maximizing load. Synchrophasors (PMUs) provide real-time measurements of electricity quantities. Thus, it allows the grid to match supply and demand. While making evaluations by expert team, scales and fuzzy numbers in Table 3 are considered.

Scales for alternatives are suitable for picture fuzzy numbers: the weakest influence factor of energy investment projects have numbers (1,1, 5, 3), poor factors have numbers (2,2,4,2), normal factors have numbers (3,3,3,1), powerful have numbers (6,2,2,0), perfect have numbers (8,1,1,0). Evaluations are presented in Table 4.

Table 3
Scales and fuzzy numbers.

Scales for criteria	Scales for alternatives	Picture fuzzy numbers			
		μ	η	N	π
Very low (VL)	Weakest (W)	.1	.1	.5	.3
Low (L)	Poor (P)	.2	.2	.4	.2
Middle (M)	Normal (F)	.3	.3	.3	.1
High (H)	Powerful (G)	.6	.2	.2	0
Very high (VH)	Perfect (B)	.8	.1	.1	0

The linguistic evaluations matrix shows the link between Research and Development (criterion 1), Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects. The picture fuzzy direct relation matrix is constructed as in Table 5.

The picture fuzzy direct relation matrix shows that Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects connected with different picture fuzzy numbers. The picture fuzzy rough sets are determined in Table 6.

The picture fuzzy rough sets shows that Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects have interconnection with picture fuzzy rough sets. Table 7 gives information about calculation results of the critical values.

The picture fuzzy rough sets shows that Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects have different relationship degrees of criteria. Defuzzified relation matrix is created in Table 8.

The relation matrix is transposed so that each sum of columns equals 1. Moreover, the stable matrix is constructed by limiting powers until each row raises the stable value. Thus, each stable value of the row gives information about the criterion weight. Table 9 includes the details of the stable matrix.

Table 9 indicates that research and development (criterion 1) plays the most critical role for renewable-friendly smart grid technologies for distributed energy investment projects. On the other side, cost (criterion 3) is another essential factor for this issue. Nonetheless, commercialization (criterion 2), operational issues (criterion 4) and functionality (criterion 5) have lower importance for these projects. In the second part of the analysis, the renewable-friendly smart grid technologies are ranked with COPRAS based on PFRSs. Linguistic evaluations are shown in Table 10.

The linguistic evaluations for the renewable-friendly smart grid technologies shows that Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects are connected with Bulk Storage, Direct Current Links, Flexible Alternating Current transmission systems, Dynamic Line Ratings, Synchrophasors. Table 11 gives information about the decision matrix.

The picture fuzzy decision matrix shows that Commercialization (criterion 2), Cost (criterion 3), Operational issues (criterion 4), Functionality (criterion 5) in energy investment projects have interconnection with various group of decisions in the different way. Picture fuzzy rough sets are defined in Table 12.

Picture fuzzy rough sets shows that renewable-friendly smart grid technologies are more effective than traditional technologies in energy investment projects Normalized values are shown in Table 13.

Table 4
Linguistic evaluations for the criteria.

	C1			C2			C3			C4			C5		
	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3
Research and development (criterion 1)	–	–	–	H	H	M	M	L	L	VH	H	M	H	L	M
Commercialization (criterion 2)	M	M	VH	–	–	–	L	L	H	H	VL	VL	VL	L	L
Cost (criterion 3)	H	H	M	H	VH	H	–	–	–	M	VL	VL	L	M	M
Operational issues (criterion 4)	M	L	M	H	H	VH	VH	VH	H	–	–	–	VH	H	M
Functionality (criterion 5)	H	H	L	H	VH	M	H	H	VH	L	VL	M	–	–	–

Table 5
Picture fuzzy relation matrix.

	Decision maker 1																			
	C1				C2				C3				C4				C5			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	Π	μ	η	ν	π
C1	0	0	0	0	.6	.2	.2	0	.3	.3	.3	.1	.8	.1	.1	0	.6	.2	.2	0
C2	.3	.3	.3	.1	0	0	0	0	.2	.2	.4	.2	.6	.2	.2	0	.1	.1	.5	.3
C3	.6	.2	.2	0	.6	.2	.2	0	0	0	0	0	.3	.3	.3	.1	.2	.2	.4	.2
C4	.3	.3	.3	.1	.6	.2	.2	0	.8	.1	.1	0	0	0	0	0	.8	.1	.1	0
C5	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.2	.2	.4	.2	0	0	0	0
	Decision maker 2																			
	C1				C2				C3				C4				C5			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π
C1	0	0	0	0	.6	.2	.2	0	.2	.2	.4	.2	.6	.2	.2	0	.2	.2	.4	.2
C2	.3	.3	.3	.1	0	0	0	0	.2	.2	.4	.2	.1	.1	.5	.3	.2	.2	.4	.2
C3	.6	.2	.2	0	.8	.1	.1	0	0	0	0	0	.1	.1	.5	.3	.3	.3	.3	.1
C4	.2	.2	.4	.2	.6	.2	.2	0	.8	.1	.1	0	0	0	0	0	.6	.2	.2	0
C5	.6	.2	.2	0	.8	.1	.1	0	.6	.2	.2	0	.1	.1	.5	.3	0	0	0	0
	Decision maker 3																			
	C1				C2				C3				C4				C5			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π
C1	0	0	0	0	.3	.3	.3	.1	.2	.2	.4	.2	.3	.3	.3	.1	.3	.3	.3	.1
C2	.8	.1	.1	0	0	0	0	0	.6	.2	.2	0	.1	.1	.5	.3	.2	.2	.4	.2
C3	.3	.3	.3	.1	.6	.2	.2	0	0	0	0	0	.1	.1	.5	.3	.3	.3	.3	.1
C4	.3	.3	.3	.1	.8	.1	.1	0	.6	.2	.2	0	0	0	0	0	.3	.3	.3	.1
C5	.2	.2	.4	.2	.3	.3	.3	.1	.8	.1	.1	0	.3	.3	.3	.1	0	0	0	0

Table 6
Picture fuzzy rough sets.

	C1	C2	C3	C4	C5
C1	(⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋)	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)
C2	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋)	(⌈.2, .6⌋, ⌈.2, .2⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.1, .6⌋, ⌈.1, .2⌋, ⌈.2, .5⌋, ⌈0, .3⌋)	(⌈.1, .2⌋, ⌈.1, .2⌋, ⌈.4, .5⌋, ⌈.2, .3⌋)
C3	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋)	(⌈.1, .3⌋, ⌈.1, .3⌋, ⌈.3, .5⌋, ⌈.1, .3⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)
C4	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋)	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)
C5	(⌈.2, .6⌋, ⌈.2, .2⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.1, .3⌋, ⌈.1, .3⌋, ⌈.3, .5⌋, ⌈.1, .3⌋)	(⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋, ⌈0, 0⌋)

Normalized values shows that renewable-friendly smart grid technologies are more effective than traditional technologies in energy investment projects. Weighted decision matrix is constructed in Table 14.

Weighted decision matrix shows that renewable-friendly smart grid technologies are more effective than traditional technologies in energy investment projects Defuzzification process is implemented in Table 15.

The stable matrix is constructed by limiting powers until each row raises the stable value. It confirms that renewable-friendly smart grid technologies are more effective than traditional technologies in energy investment projects. Relative significance values and the utility index are computed in Table 16.

Table 16 demonstrates that direct current links (DC) is the most important renewable-friendly smart grid technology alternative. Additionally, dynamic line ratings (DLR) also play an essential role for this purpose. Nevertheless, Synchrophasors (PMUs) and flexible alternating current transmission systems (FACTS) are on the last ranks.

This analysis develops on the topic of renewable-friendly smart grid technologies regarding the distributed energy investment projects by using a hybrid picture fuzzy rough decision-making approach. At first, criteria are selected based on literature examination with respect to the renewable-friendly smart grid technologies for distributed energy investment projects. The M-SWARA method based on PFRSs are considered to weight

Table 7
$\tilde{s}_j$, $\tilde{k}_j$, $\tilde{q}_j$, and $\tilde{w}_j$ values for the relationship degrees of criteria.

Relationship order	$\tilde{s}_j$	$\tilde{k}_j$	$\tilde{q}_j$	$\tilde{w}_j$
C1				
C4		(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈.33, .43⌋, ⌈.32, .35⌋, ⌈.32, .36⌋, ⌈.25, .30⌋)
C2	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈1.3, 1.6⌋, ⌈1.2, 1.3⌋, ⌈1.2, 1.3⌋, ⌈1, 1.1⌋)	(⌈.62, .76⌋, ⌈.76, .83⌋, ⌈.76, .83⌋, ⌈.90, 1⌋)	(⌈.26, .26⌋, ⌈.26, .27⌋, ⌈.27, .28⌋, ⌈.25, .27⌋)
C5	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈1.2, 1.6⌋, ⌈1.2, 1.3⌋, ⌈1.2, 1.4⌋, ⌈1, 1.2⌋)	(⌈.39, .64⌋, ⌈.59, .69⌋, ⌈.54, .69⌋, ⌈.75, 1⌋)	(⌈.16, .21⌋, ⌈.21, .22⌋, ⌈.20, .22⌋, ⌈.22, .25⌋)
C3	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈1.2, 1.3⌋, ⌈1.2, 1.3⌋, ⌈1.3, 1.4⌋, ⌈1.1, 1.2⌋)	(⌈.30, .53⌋, ⌈.45, .57⌋, ⌈.39, .53⌋, ⌈.63, .90⌋)	(⌈.12, .18⌋, ⌈.16, .18⌋, ⌈.14.17⌋, ⌈.19, .23⌋)
C2				
C1		(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈.30, .42⌋, ⌈.30, .32⌋, ⌈.33, .39⌋, ⌈.26, .33⌋)
C3	(⌈.2, .6⌋, ⌈.2, .2⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈1.2, 1.6⌋, ⌈1.2, 1.2⌋, ⌈1.2, 1.4⌋, ⌈1, 1.2⌋)	(⌈.62, .83⌋, ⌈.83, .83⌋, ⌈.71, .83⌋, ⌈.83, 1⌋)	(⌈.25, .26⌋, ⌈.25, .26⌋, ⌈.27, .28⌋, ⌈.26, .28⌋)
C4	(⌈.1, .6⌋, ⌈.1, .2⌋, ⌈.2, .5⌋, ⌈0, .3⌋)	(⌈1.1, 1.6⌋, ⌈1.1, 1.2⌋, ⌈1.2, 1.5⌋, ⌈1, 1.3⌋)	(⌈.39, .75⌋, ⌈.69, .75⌋, ⌈.47, .69⌋, ⌈.64, 1⌋)	(⌈.16, .23⌋, ⌈.22, .23⌋, ⌈.18, .22⌋, ⌈.21, .26⌋)
C5	(⌈.1, .2⌋, ⌈.1, .2⌋, ⌈.4, .5⌋, ⌈.2, .3⌋)	(⌈1.1, 1.2⌋, ⌈1.1, 1.2⌋, ⌈1.4, 1.5⌋, ⌈1.2, 1.3⌋)	(⌈.32, .68⌋, ⌈.57, .68⌋, ⌈.31, .49⌋, ⌈.491, .83⌋)	(⌈.13, .20⌋, ⌈.18, .20⌋, ⌈.12, .16⌋, ⌈.16, .21⌋)
C3				
C2		(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈.33, .40⌋, ⌈.31, .35⌋, ⌈.33, .37⌋, ⌈.26, .30⌋)
C1	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈1.3, 1.6⌋, ⌈1.2, 1.3⌋, ⌈1.2, 1.3⌋, ⌈1, 1.1⌋)	(⌈.62, .76⌋, ⌈.76, .83⌋, ⌈.76, .83⌋, ⌈.90, 1⌋)	(⌈.25, .25⌋, ⌈.26, .27⌋, ⌈.28, .28⌋, ⌈.26, .27⌋)
C5	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈1.2, 1.3⌋, ⌈1.2, 1.3⌋, ⌈1.3, 1.4⌋, ⌈1.1, 1.2⌋)	(⌈.48, .64⌋, ⌈.59, .69⌋, ⌈.54, .64⌋, ⌈.75, .90⌋)	(⌈.19, .21⌋, ⌈.21, .22⌋, ⌈.20, .21⌋, ⌈.23, .24⌋)
C4	(⌈.1, .3⌋, ⌈.1, .3⌋, ⌈.3, .5⌋, ⌈.1, .3⌋)	(⌈1.1, 1.3⌋, ⌈1.1, 1.3⌋, ⌈1.3, 1.5⌋, ⌈1.1, 1.3⌋)	(⌈.36, .58⌋, ⌈.45, .63⌋, ⌈.36, .49⌋, ⌈.58, .82⌋)	(⌈.14, .19⌋, ⌈.16, .19⌋, ⌈.13, .16⌋, ⌈.17, .22⌋)
C4				
C2		(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈.39, .47⌋, ⌈.29, .33⌋, ⌈.29, .34⌋, ⌈.25, .27⌋)
C3	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈1.6, 1.8⌋, ⌈1.1, 1.2⌋, ⌈1.1, 1.2⌋, ⌈1, 1⌋)	(⌈.55, .62⌋, ⌈.83, .90⌋, ⌈.83, .90⌋, ⌈1, 1⌋)	(⌈.24, .26⌋, ⌈.26, .28⌋, ⌈.26, .28⌋, ⌈.25, .27⌋)
C5	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈1.3, 1.8⌋, ⌈1.1, 1.3⌋, ⌈1.1, 1.3⌋, ⌈1, 1.1⌋)	(⌈.30, .48⌋, ⌈.64, .82⌋, ⌈.64, .82⌋, ⌈.90, 1⌋)	(⌈.14, .19⌋, ⌈.21, .24⌋, ⌈.21, .24⌋, ⌈.24, .25⌋)
C1	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈1.2, 1.3⌋, ⌈1.2, 1.3⌋, ⌈1.3, 1.4⌋, ⌈1.1, 1.2⌋)	(⌈.23, .40⌋, ⌈.49, .68⌋, ⌈.45, .63⌋, ⌈.75, .90⌋)	(⌈.11, .15⌋, ⌈.16, .20⌋, ⌈.15, .18⌋, ⌈.20, .23⌋)
C5				
C3		(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋, ⌈1, 1⌋)	(⌈.33, .46⌋, ⌈.29, .34⌋, ⌈.30, .37⌋, ⌈.25, .30⌋)
C2	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈1.3, 1.8⌋, ⌈1.1, 1.3⌋, ⌈1.1, 1.3⌋, ⌈1, 1.1⌋)	(⌈.55, .76⌋, ⌈.76, .90⌋, ⌈.76, .90⌋, ⌈.90, 1⌋)	(⌈.25, .25⌋, ⌈.26, .27⌋, ⌈.27, .28⌋, ⌈.25, .27⌋)
C1	(⌈.2, .6⌋, ⌈.2, .2⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈1.2, 1.6⌋, ⌈1.2, 1.2⌋, ⌈1.2, 1.4⌋, ⌈1, 1.2⌋)	(⌈.34, .64⌋, ⌈.64, .75⌋, ⌈.54, .75⌋, ⌈.75, 1⌋)	(⌈.16, .21⌋, ⌈.22, .22⌋, ⌈.20, .23⌋, ⌈.23, .25⌋)
C4	(⌈.1, .3⌋, ⌈.1, .3⌋, ⌈.3, .5⌋, ⌈.1, .3⌋)	(⌈1.1, 1.3⌋, ⌈1.1, 1.3⌋, ⌈1.3, 1.5⌋, ⌈1.1, 1.3⌋)	(⌈.26, .58⌋, ⌈.49, .68⌋, ⌈.36, .58⌋, ⌈.58, .90⌋)	(⌈.12, .19⌋, ⌈.16, .20⌋, ⌈.13, .17⌋, ⌈.17, .23⌋)

Table 8
Defuzzified matrix.

	C1	C2	C3	C4	C5
C1	.00	.27	.17	.35	.21
C2	.34	.00	.26	.22	.19
C3	.26	.34	.00	.18	.22
C4	.17	.37	.26	.00	.20
C5	.21	.26	.35	.18	.00

Table 9
Stable matrix.

	C1	C2	C3	C4	C5
C1	.20	.20	.20	.20	.20
C2	.24	.24	.24	.24	.24
C3	.21	.21	.21	.21	.21
C4	.19	.19	.19	.19	.19
C5	.17	.17	.17	.17	.17

these items. After that, different alternatives are ranked based on the renewable-friendly smart grid technologies with COPRAS technique by using PFRS. It is determined that research and development play the most critical role with respect to the renewable-friendly smart grid technologies for distributed energy investment projects. On the other side, cost is another essential

Table 10
Linguistic evaluations for the renewable-friendly smart grid technologies.

	Bulk storage			Direct current links			Flexible alternating current transmission systems			Dynamic line ratings			Synchrophasors		
	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3
Criterion 1	G	F	G	B	G	B	B	B	G	F	G	P	F	P	F
Criterion 2	B	G	G	B	G	G	B	G	B	F	P	F	G	F	W
Criterion 3	G	F	F	B	G	G	B	G	B	F	G	P	P	P	W
Criterion 4	F	G	P	B	G	F	B	G	G	F	F	P	P	G	F
Criterion 5	G	G	F	G	G	F	B	G	G	F	G	P	P	F	P

Table 11
Picture fuzzy decision matrix.

Decision maker 1																				
	BS				DC				FACTS				DLR				PMUs			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	Π	μ	η	ν	π
C1	.6	.2	.2	0	.8	.1	.1	0	.8	.1	.1	0	.3	.3	.3	.1	.3	.3	.3	.1
C2	.8	.1	.1	0	.8	.1	.1	0	.8	.1	.1	0	.3	.3	.3	.1	.6	.2	.2	0
C3	.6	.2	.2	0	.8	.1	.1	0	.8	.1	.1	0	.3	.3	.3	.1	.2	.2	.4	.2
C4	.3	.3	.3	.1	.8	.1	.1	0	.8	.1	.1	0	.3	.3	.3	.1	.2	.2	.4	.2
C5	.6	.2	.2	0	.6	.2	.2	0	.8	.1	.1	0	.3	.3	.3	.1	.2	.2	.4	.2
Decision maker 2																				
	BS				DC				FACTS				DLR				PMUs			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π
C1	.3	.3	.3	.1	.6	.2	.2	0	.8	.1	.1	0	.6	.2	.2	0	.2	.2	.4	.2
C2	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.2	.2	.4	.2	.3	.3	.3	.1
C3	.3	.3	.3	.1	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.2	.2	.4	.2
C4	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.3	.3	.3	.1	.6	.2	.2	0
C5	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.6	.2	.2	0	.3	.3	.3	.1
Decision maker 3																				
	BS				DC				FACTS				DLR				PMUs			
	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π	μ	η	ν	π
C1	.6	.2	.2	0	.8	.1	.1	0	.6	.2	.2	0	.2	.2	.4	.2	.3	.3	.3	.1
C2	.6	.2	.2	0	.6	.2	.2	0	.8	.1	.1	0	.3	.3	.3	.1	.1	.1	.5	.3
C3	.3	.3	.3	.1	.6	.2	.2	0	.8	.1	.1	0	.2	.2	.4	.2	.1	.1	.5	.3
C4	.2	.2	.4	.2	.3	.3	.3	.1	.6	.2	.2	0	.2	.2	.4	.2	.3	.3	.3	.1
C5	.3	.3	.3	.1	.3	.3	.3	.1	.6	.2	.2	0	.2	.2	.4	.2	.2	.2	.4	.2

Table 12
Picture fuzzy rough sets.

	BS	DC	FACTS	DLR	PMUs
C1	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)
C2	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈.1, .6⌋, ⌈.1, .3⌋, ⌈.2, .5⌋, ⌈0, .3⌋)
C3	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.1, .2⌋, ⌈.1, .2⌋, ⌈.4, .5⌋, ⌈.2, .3⌋)
C4	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.3, .8⌋, ⌈.1, .3⌋, ⌈.1, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)
C5	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.3, .6⌋, ⌈.2, .3⌋, ⌈.2, .3⌋, ⌈0, .1⌋)	(⌈.6, .8⌋, ⌈.1, .2⌋, ⌈.1, .2⌋, ⌈0, 0⌋)	(⌈.2, .6⌋, ⌈.2, .3⌋, ⌈.2, .4⌋, ⌈0, .2⌋)	(⌈.2, .3⌋, ⌈.2, .3⌋, ⌈.3, .4⌋, ⌈.1, .2⌋)

Table 13
Normalized values.

	BS	DC	FACTS	DLR	PMUs
C1	(⌈.375, .75⌋, ⌈.25, .375⌋, ⌈.25, .375⌋, ⌈0, .125⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.25, .75⌋, ⌈.25, .375⌋, ⌈.25, .5⌋, ⌈0, .25⌋)	(⌈.25, .375⌋, ⌈.25, .375⌋, ⌈.375, .5⌋, ⌈.125, .25⌋)
C2	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.25, .375⌋, ⌈.25, .375⌋, ⌈.375, .5⌋, ⌈.125, .25⌋)	(⌈.125, .75⌋, ⌈.125, .375⌋, ⌈.25, .625⌋, ⌈0, .375⌋)
C3	(⌈.375, .75⌋, ⌈.25, .375⌋, ⌈.25, .375⌋, ⌈0, .125⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.25, .75⌋, ⌈.25, .375⌋, ⌈.25, .5⌋, ⌈0, .25⌋)	(⌈.125, .25⌋, ⌈.125, .25⌋, ⌈.5, .625⌋, ⌈.25, .375⌋)
C4	(⌈.25, .75⌋, ⌈.25, .375⌋, ⌈.25, .5⌋, ⌈0, .25⌋)	(⌈.375, 1⌋, ⌈.125, .375⌋, ⌈.125, .375⌋, ⌈0, .125⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.25, .375⌋, ⌈.25, .375⌋, ⌈.375, .5⌋, ⌈.125, .25⌋)	(⌈.25, .75⌋, ⌈.25, .375⌋, ⌈.25, .5⌋, ⌈0, .25⌋)
C5	(⌈.375, .75⌋, ⌈.25, .375⌋, ⌈.25, .375⌋, ⌈0, .125⌋)	(⌈.375, .75⌋, ⌈.25, .375⌋, ⌈.25, .375⌋, ⌈0, .125⌋)	(⌈.75, 1⌋, ⌈.125, .25⌋, ⌈.125, .25⌋, ⌈0, 0⌋)	(⌈.25, .75⌋, ⌈.25, .375⌋, ⌈.25, .5⌋, ⌈0, .25⌋)	(⌈.25, .375⌋, ⌈.25, .375⌋, ⌈.375, .5⌋, ⌈.125, .25⌋)

factor in this issue. Nonetheless, operational issues and functionality have lower importance for these projects. It is also concluded that direct current links (DC) is the most important renewable-friendly smart grid technology alternative. Additionally, dynamic

Table 14
Weighted decision matrix.

	BS	DC	FACTS	DLR	PMUs
C1	(⌈.07, .15⌋, ⌈.05, .07⌋, ⌈.05, .07⌋, ⌈0, .02⌋)	(⌈.05, .07⌋, ⌈0, .05⌋, ⌈.07, .15⌋, ⌈.02, .07⌋)	(⌈.10, .20⌋, ⌈.05, .15⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.05, .15⌋, ⌈.05, .07⌋, ⌈.05, .10⌋, ⌈0, .05⌋)	(⌈.05, .07⌋, ⌈.05, .07⌋, ⌈.07, .10⌋, ⌈.02, .05⌋)
C2	(⌈.17, .23⌋, ⌈.02, .05⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.17, .23⌋, ⌈.02, .05⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.17, .23⌋, ⌈.02, .05⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.05, .08⌋, ⌈.05, .08⌋, ⌈.08, .11⌋, ⌈.02, .05⌋)	(⌈.02, .17⌋, ⌈.02, .08⌋, ⌈.05, .14⌋, ⌈0, .08⌋)
C3	(⌈.07, .15⌋, ⌈.05, .07⌋, ⌈.05, .07⌋, ⌈0, .02⌋)	(⌈.15, .20⌋, ⌈.02, .05⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.15, .20⌋, ⌈.02, .05⌋, ⌈.02, .05⌋, ⌈0, 0⌋)	(⌈.05, .15⌋, ⌈.05, .07⌋, ⌈.05, .10⌋, ⌈0, .05⌋)	(⌈.02, .05⌋, ⌈.02, .05⌋, ⌈.10, .12⌋, ⌈.05, .07⌋)
C4	(⌈.04, .14⌋, ⌈.04, .07⌋, ⌈.04, .09⌋, ⌈0, .04⌋)	(⌈.07, .18⌋, ⌈.02, .07⌋, ⌈.02, .07⌋, ⌈0, .02⌋)	(⌈.14, .18⌋, ⌈.02, .04⌋, ⌈.02, .04⌋, ⌈0, 0⌋)	(⌈.04, .07⌋, ⌈.04, .07⌋, ⌈.07, .09⌋, ⌈.02, .04⌋)	(⌈.04, .14⌋, ⌈.04, .07⌋, ⌈.04, .09⌋, ⌈0, .04⌋)
C5	(⌈.06, .12⌋, ⌈.04, .06⌋, ⌈.04, .06⌋, ⌈0, .02⌋)	(⌈.06, .12⌋, ⌈.04, .06⌋, ⌈.04, .06⌋, ⌈0, .02⌋)	(⌈.12, .16⌋, ⌈.02, .04⌋, ⌈.02, .04⌋, ⌈0, 0⌋)	(⌈.04, .12⌋, ⌈.04, .06⌋, ⌈.04, .08⌋, ⌈0, .04⌋)	(⌈.04, .06⌋, ⌈.04, .06⌋, ⌈.06, .08⌋, ⌈.02, .04⌋)

Table 15
Defuzzified decision matrix.

	BS	DC	FACTS	DLR	PMUs
C1	.15	.19	.19	.14	.11
C2	.23	.23	.23	.13	.16
C3	.15	.20	.20	.15	.09
C4	.14	.16	.18	.11	.14
C5	.13	.13	.16	.12	.09

Table 16
Relative significance, utility index, and ranking results for the alternatives.

	Q_i	U_i	Ranking
BS	.76	84.6	3
DC	.90	10.0	1
FACTS	.74	82.0	4
DLR	.79	87.7	2
PMUs	.71	78.9	5

line ratings (DLR) also play an essential role for this purpose. Nevertheless, synchrophasors (PMUs) and flexible alternating current transmission systems (FACTS) are among the last ranks.

To increase the efficiency of smart grid systems, priority should be given to the development of research and development studies on renewable energies. In this context, comprehensive planning should be made for these studies. In this way, it will be possible to increase the efficiency of the conducted work. Within the scope of these studies, new technologies for RWJ types should be focused on. In this context, new technologies for all RWJ alternatives should be followed comprehensively. For example, bifacial solar energy panels have permeability. In this way, these panels can convert the sun rays falling behind and reflected back into electrical energy. This increases the efficiency of the obtained smart grid systems. Sun et al. (2018), Hu et al. (2021) and Song et al. (2020) also identified that bifacial solar energy panels have a powerful influence on the development of the energy efficiency so that researchers should mainly focus on this issue to improve the smart grid systems.

On the other hand, wind panels installed on the sea also help increase electricity production. In this context, increasing research and development for such investments will also make smart grid systems more successful. In addition to these, there is a need for new applications that will increase the efficiency of RWJ types. In this context, it would be appropriate for countries to pay particular attention to this issue in their research and development studies and programs. DeCastro et al. (2019) underlined that offshore wind energy projects should be improved. Moreover, Costoya et al. (2020) and da Silva Santos and Barros (2019) also defined that offshore wind energy projects have a significant contribution to the efficiency of smart grid systems.

5. Discussion

Recent studies show that distributed energy investment projects respond to innovation processes, economic growth, and energy markets. Emerging and developed economies are confronted with volatility of exchange rates and its major impact on exports, volume of country investments, growth of employment in the country, inflation, output growth rate on international trade and more specifically on the economic activity in the country (Sim and Kim, 2019; Qiu et al., 2019).

The available literature on distributed energy investment projects does not provide clear conclusions on whether the impact of volatility on the FX market is positive, negative or both. Many studies examine distributed energy investment projects. In the empirical findings of previous studies, the net effect of renewable-friendly smart grid technologies is inconsistent. Theoretically, the inconclusiveness is due to the different attitudes towards risk of international traders. Some are risk-averse while some are risk-loving. Risk-averse traders substitute international trade with domestic trade to avoid exchange rate volatility. While risk-loving investors increase international trade to earn a higher profit as compensation in case of the favourable effects of renewable-friendly smart grid technologies on trade flows. This factor differs depending on the scope of the study and its analysed market, thus requiring more disaggregated trade data for future research (Han et al., 2020). The relationship between renewable-friendly smart grid technologies and distributed energy investment projects among nations has been studied through various empirical approaches. Existing literature is subject to any of the following constraints. Firstly, earlier studies applied aggregated trade data of a country with the remaining world. The results of these studies are mixed. Secondly, due to the problems of aggregation bias, later studies disaggregate data at the bilateral level. The second flow of recent studies took imports and exports separately to overcome the problem of aggregation bias: these studies disaggregate data not only just at a country level but also at the industry level and in some cases even at the product level. From an econometric aspect, previous studies used various analysis techniques that recent research conclude inappropriate. These studies used methods that do not account for mixed integration cases (Adedoyin et al., 2020).

6. Conclusions

Research and development studies are critical regarding the discussed issue. Private sector companies have a very important role in this process. Companies' analyses on RWJ technologies contribute to reducing the costs of these projects. Sim and Kim (2019) and Qiu et al. (2019) identified that companies should mainly conduct research and development works for the improvements of the RWJ investment technologies. However, these measures may not be sufficient, i.e., these studies should not be conducted only by private sector companies. In this context, government bodies should also play an active role in this process. For this purpose, incentives given by governments to RWJ research and development studies should be increased and improved. Han et al. (2020) and Adedoyin et al. (2020) also stated that government support plays an essential role regarding the improvement of research and development activities for RWJ technologies.

The most significant novelty of this study is providing essential solutions to improve renewable-friendly smart grid technologies for the distributed energy investment projects with a novel hybrid picture fuzzy rough decision-making approach. However, in this study, only important criteria and smart grid technology are presented. In other words, a case study has not been conducted in the industry to understand the impact of the analysis results. In future examinations, industrial implications can be made to understand this situation. In addition, in this study, it is recommended to develop new technologies that will increase research and development studies improving the efficiency of smart grid systems. However, no information is given about how this new technology will be implemented. Therefore, a specific focus on the development of new technologies in new reviews helps improve the performance of these projects.

Due to mixed and inappropriate findings of previous studies, research papers used disaggregated trade data for each trading partner at the industry level to conclude more accurate results and policy recommendations for each market participant. The panel framework compared the effects of renewable-friendly smart grid technologies on distributed energy investment projects of developed and emerging economies. The study concludes that distributed energy investment projects in developing economies are more sensitive to the volatility of the exchange rate.

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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