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# A novel fuzzy decision-making approach to pension fund investments in renewable energy

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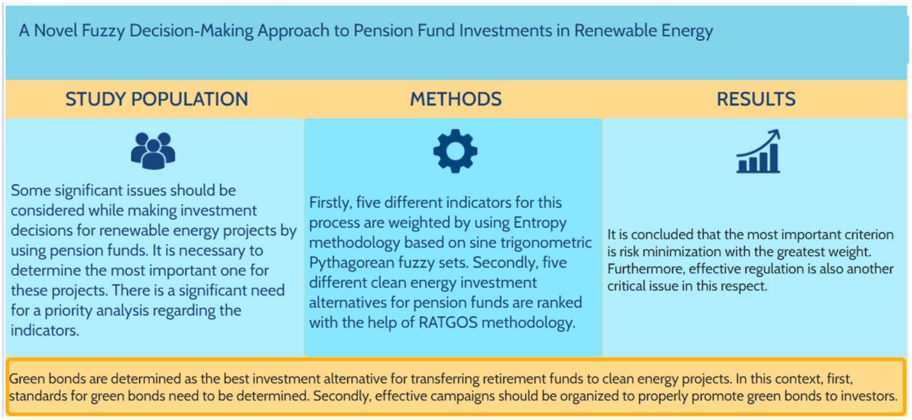
**Abstract**

Pension fund must consider some significant issues when making renewable energy project investment decisions. It is necessary to determine the most important factors and prioritize the indicators. Accordingly, the purpose of this study is to conduct a priority analysis of the determinants of investment in renewable energy projects by pension funds. This study constructs a novel fuzzy decision-making model. First, five indicators for this process are weighted using an entropy methodology based on sine trigonometric Pythagorean fuzzy sets. The CRITIC methodology is also considered to make a comparative evaluation. Second, five different clean energy investment alternatives for pension funds are ranked using the RATGOS methodology. Similarly, this ranking analysis is also made by considering TOPSIS technique to check the reliability of the results. The main contribution of this study is the creation of a new and comprehensive fuzzy decision-making model to identify the most important factors in renewable energy project investments for pension funds. The proposed model uses the RATGOS technique to rank clean energy investment alternatives for pension funds. By considering the geometrical mean in the RATGOS calculation process, criticisms related to existing ranking techniques can be overcome. The use of sine trigonometric Pythagorean fuzzy numbers provides significant benefits to the quality of the proposed decision-making model. The defuzzification process can be implemented appropriately using these sets. Therefore, this study's findings pave the way for investors to make investment decisions under these circumstances. It is concluded that the most important criterion is risk minimization. Effective regulations are another critical issue. Furthermore, the ranking results indicate that the most suitable renewable energy alternative is green bonds. The comparative results with STPFY-TOPSIS show that the proposed model generates coherent and reliable findings.

**Keywords:** Pension funds, Financial innovation, Energy investments, Clean energy

**Graphical abstract**




## Introduction

Pension funds are financial intermediaries that provide income to retired individuals. These funds invest in broad portfolios that cover different investment instruments. This diversification makes it possible to minimize portfolio risk. This situation contributes significantly to investment stability. Pension funds include long-term investments (Aburto Barrera and Wagner 2023). The biggest advantage of this situation is that individuals can save large amounts during this time. Another advantage of pension funds is the tax advantages, which increase the amount of investors' savings. Financial experts manage savings in pension funds. Thus, the probability of increasing the revenue is much higher. Pension funds play an important role in developing a country's financial markets. These funds generate investments in instruments such as bonds and stocks (Bouteska et al. 2023). This condition helps to increase liquidity in financial markets. Moreover, because these funds are long-term investments, they contribute to increasing financial market stability. Similarly, these funds can provide a significant amount of resources for investment in a country. This contributes significantly to economic growth.

It is possible to make different types of investments using pension funds. Pension fund managers propose an asset allocation policy that considers investors' risk profiles. Some issues need to be considered before this process can be carried out effectively. First, it is necessary to pay attention to risk tolerance and investment objectives. In this context, if it is desirable to take more risk, then the investment portfolio can hold more stocks (Harrison et al. 2023). On the contrary, in cases where it is not desirable to take too much risk, more focus should be placed on financial instruments such as government bonds. Moreover, the rate of return should be considered when deciding which investment instruments to use in pension funds. Because this situation can increase the success of a portfolio, it also helps ensure customer satisfaction. Thus, it is possible to increase the demand for pension funds significantly. Another important aspect of this process is successful portfolio diversification (Bonizzi et al. 2023). The presence of different types of instruments in the investment portfolio significantly helps minimize possible risks.

Renewable energy investments are also examples of projects for which pension funds can be evaluated. One of the most important advantages of these projects is that they contribute to reducing environmental pollution. However, with renewable energy investments, the obligation of countries to import energy has been eliminated (Martínez et al. 2023). Within this framework, direct investments can be made in energy types such as wind turbines or solar panels with pension funds. However, because these projects are long term, their risks are quite high. Similarly, these funds can focus on sustainable infrastructure investments. This situation strongly contributes to the development of renewable energy technologies (Kou et al. 2023a, b). Yieldcos offer similar opportunities by operating clean energy assets. In addition, it is possible to invest in renewable energy with a lower pension fund risk. For example, green bonds can be purchased to achieve this objective. Because of this instrument, fixed-income loans can be provided to renewable energy projects. This significantly reduces investment risks. In other words, even if these projects do not make the desired profit, they must pay bondholders a fixed amount (Carayannis et al. 2023).

To decide whether to invest in renewable energy projects with pension funds, certain issues need to be considered. First, attention should be paid to the risk status of the investment types. Similarly, the expected returns of the investment types are important in this process. Financial support offered by governments should also be considered in renewable energy investment decisions (Kou et al. 2022). When transferring pension funds to renewable energy projects, investment decisions should consider the importance of these issues. Therefore, it is necessary to determine the most important factors for renewable energy projects (Li et al. 2022). However, only a few studies concentrate on this issue. In this context, there is a significant need to analyze the priority of the factors in renewable energy investment decisions for pension funds.

Accordingly, this study aims to identify the key determinants of investment to renewable energy projects using pension funds. Thus, the research question is which issues should pension funds pay attention to while investing in clean energy, and which renewable energy investment type is the most suitable for this process. A novel fuzzy decision-making model is constructed to answer this question. First, five indicators for this process are weighted using an entropy methodology based on sine trigonometric Pythagorean fuzzy sets. The CRITIC methodology is also considered to make a comparative evaluation. Second, five different clean energy investment alternatives for pension funds were ranked using the RATGOS methodology. Similarly, this analysis is performed by considering the TOPSIS technique to check the reliability of the ranking results. The main motivation of this study is the need for a comprehensive evaluation of the key determinants of investment to renewable energy projects using pension funds. Different methodologies, such as the balanced scorecard and PESTEL, can be considered in this framework. In such situations, decision-making models are preferred. However, these models have certain limitations. Therefore, a novel model that can overcome these limitations is required.

The main contribution of this study is the creation of a new and comprehensive fuzzy decision-making model to identify the most important factors in renewable energy project investments for pension funds. The proposed model has some advantages over existing models. First, the main methodological contribution of this study is that the

RATGOS technique is considered a multi-criteria decision-making model. Although there are many methods in the literature for creating alternative rankings, these approaches have been criticized for several reasons. For instance, the Euclidean distance is considered in the TOPSIS methodology by computing the distances to negative ideal solutions (de Oliveira et al. 2024). However, this approach has been criticized for generating inappropriate results (Qian et al. 2023; Patel et al. 2023). Similarly, the ARAS method considers the optimal sum ratio of the sum of the alternatives (Goswami et al. 2021). Alternatively, averaging the optimal ratio for each criterion may yield more accurate results (Goswami et al. 2022). However, these issues have been strongly criticized in the literature. This situation explains the significant need for a new ranking technique. Nevertheless, to overcome these criticisms, Dinçer et al. (2023) proposed a novel ranking model called RATGOS that considers the geometrical mean in the analysis process. Owing to these advantages, the RATGOS technique was used in the proposed model to rank clean energy investment alternatives for pension funds. Second, The use of sine trigonometric Pythagorean fuzzy numbers significantly improves the quality of the proposed decision-making model. The defuzzification process can be appropriately implemented using these sets (Akram et al. 2023). This condition has a positive influence on overcoming uncertainty in the evaluation process. Furthermore, in triangular fuzzy numbers, the membership values increased or decreased linearly. This situation requires that the evaluation scales increase linearly. However, because sine trigonometric numbers consider the sine curve, they reflect linguistic expression transitions in expert evaluations more realistically. This enabled us to obtain more realistic results. Therefore, by considering these sets, more effective solutions can be presented for investment decisions on renewable energy alternatives by pension funds (Garg et al. 2023).

A literature review is presented in the second part. The methodology of the study is explained in the third section. The results of the proposed model are presented in the fourth section. The discussion and concluding remarks are presented in the final sections.

## Literature review

Investing in a project or financial instrument involves several considerations for pension funds. One aspect is the compatibility of investments with funds' risk–return profiles (Gutierrez et al. 2019). Like any infrastructure investment, renewable energy projects carry risks that can result in high costs if they are not managed efficiently (Kul et al. 2020). These costs may prevent pension funds from fulfilling their liabilities. However, as long-term investors, pension funds must also provide a stable income stream for retirees (Balsalobre-Lorente et al. 2023). Investing in low-risk instruments can cause pension funds to miss alternative returns and depreciate their assets over time (Martí-Ballester 2020). Pension funds must balance risk and return when making investment decisions and pursue a sustainable strategy that aligns with their financial goals. Incentives and subsidies can be effective tools for pension funds to encourage clean energy investments by mitigating risk and enhancing returns. According to Sendstad et al. (2022), a stable policy environment is crucial for incentivizing renewable energy investments. Government guarantees can effectively offset the political and legal risks related to clean energy projects while providing a more stable revenue stream. Peksevim and Ercan (2023) also stated that fiscal incentives such as tax rebates, discounts, and grants can increase clean energy projects' risk-adjusted returns, making them more appealing to pension funds. Consequently, incentives and subsidies play a crucial role in pension funds' investment decisions regarding clean energy.

Pension funds may have strict regulations that affect investment strategies. Compliance with legal regulations is one of the investors' most important evaluation criteria (Sun et al. 2023). Thus, pension funds are not free to make unlimited investment decisions due to investment constraints such as solvency rules (IRENA 2020). In most cases, compliance with the relevant legislation is a prerequisite for investment decisions. Consequently, pension funds tend to rely more on traditional asset classes, such as stocks and bonds, for their portfolios, while the proportion of infrastructure investments is extremely low (OECD 2023). Lack of expertise and knowledge is another main obstacle preventing pension funds from investing in clean energy. Fiori Maccioni (2023) found that evaluating clean energy investments can be complex and requires internal capacity. However, portfolios and indirect investments are asset classes in which pension funds can be assessed more easily (Defau and De Moor 2021). Therefore, an essential criterion that affects investment decisions is the compatibility of an investment instrument with its internal capabilities.

Investing in clean energy presents opportunities for pension funds to diversify their assets and generate long-term returns (Taghizadeh-Hesary and Yoshino 2020). Pension funds have several investment alternatives, including direct investments in clean energy projects. Direct investment allows for greater control over investment, but requires extensive knowledge and involves higher risk (Binkley et al. 2020; Wang et al. 2023). Alternatively, clean energy funds offer diverse investment opportunities that require less expertise. These funds invest in a range of clean energy assets, making them more easily investable, scalable, and liquid than direct investments (Sartzetakis 2021). To meet their ongoing obligations, pension funds require a steady income stream that is both long term and consistent. Yieldcos are companies that operate renewable energy assets such as solar and wind, and offer investors predictable cash flows in the long term. By investing in Yieldcos, pension funds can diversify their portfolios of clean energy assets while minimizing operational costs compared to direct investments (Polzin and Sanders 2020). Green bonds are another option to generate predictable cash flows for pension funds. These fixed-income securities are issued to finance projects with positive environmental impacts (Seran et al. 2023). Green bonds are a suitable alternative for institutional investors because they provide a stable income stream with relatively low risk (Sangiorgi and Schopohl 2021).

Finally, sustainable infrastructure investments allow pension funds to diversify their clean energy investment portfolios. These investments are typically made by public institutions that focus on energy efficiency. They can provide pension funds with long-term cash flows aided by government incentives and subsidies (Mastrogiacomo et al. 2023). However, these investments are complex and similar to direct clean energy investments (Sengupta et al. 2018). In conclusion, the literature review reveals a range of investment alternatives for pension funds for clean energy. However, each investment has its own advantages and disadvantages. Fragnière et al.

(2023) concluded that pension funds can play a key role in supporting the transition to clean energy by investing in renewable energy assets. This approach would not only provides sustainable and diversified cash flows for pension funds but also strengthens their position in facilitating the shift toward renewable energy (Andersen and Dreyer 2023).

Investment risk is the level of uncertainty in an investment's expected returns (Seran et al. 2023). Low-risk investments typically deliver stable, but relatively low, returns. On the other hand, high-risk investments may offer a higher potential return but come with greater uncertainty. Return refers to the financial gain an investment can achieve when it reaches maturity (Sun et al. 2023). Thus, pension funds must carefully consider the balance between risks and returns when investing in clean energy sources. Incentives and subsidies for clean energy can be crucial factors in investment decisions because they help reduce the financial burden of investing (Mastrogiacomo et al. 2023). However, the complexity of investment assets can discourage funds, particularly those lacking expertise in the field, from investing. Similarly, regulatory compliance is important for making new investment decisions and increasing existing investments (Fragnière et al. 2023). Although legal regulations can incentivize clean energy investments, they can also create barriers in certain cases (Harrison et al. 2023).

Pension funds have various options to invest in clean energy sources. They can choose to invest directly in clean energy projects, which gives them greater control but can be riskier owing to the need for specialized expertise (Carayannis et al. 2023). Another option is to invest in clean energy funds, which are a diversified portfolio of assets managed by specialized teams (Ai et al. 2023). Yieldcos also offer similar opportunities, as they operate clean energy assets and provide sustainable cash flows through long-term contracts and dividends (Cheng et al. 2023). Green bonds represent an alternative to pension funds. Public institutions and private companies issue debt securities to finance clean energy projects (Li et al. 2022). Although they offer lower returns than other options, they are at relatively low risk. Finally, pension funds can invest in sustainable infrastructure projects that reduce energy consumption and increase efficiency (Moiseev et al. 2023). These projects focus on infrastructure development in areas such as public transportation, green buildings, and waste management.

Table 10 provides a summary of the literature. The main results of the literature review are as follow. Many studies examined how pension funds evaluate investment instruments, highlighting the importance of this issue. Additionally, pension funds can also invest in renewable energy projects. Although many studies emphasized this process, a limited number of studies specify the criteria that should be considered while making this investment decision. In other words, these studies rarely focused on the most significant indicators for pension fund evaluation. This situation can be accepted as the main gap in the literature. Therefore, more important indicators of this subject should be identified. Investors can make appropriate decisions through this analysis. However, prior studies generally focused on the importance of pension funds instead of analyzing the most essential indicators. Hence, there is a need for a study to determine the key criteria to make correct investment decisions. To fill this gap, this study conducted an analysis of the priorities of the investment criteria.

## Proposed methodology

This section describes the models used in this study. The ENTROPY and CRITIC methods are used to determine the importance levels of the criteria. The RATGOS and TOPSIS methods are preferred for ranking the alternatives. In both methods, sine trigonometric Pythagorean fuzzy numbers are used.

### Sine trigonometric pythagorean fuzzy entropy

The entropy method is a multi-criteria decision-making method used to determine the importance levels of criteria. The basis of this method is the calculation of the uncertainty measure in a matrix obtained from expert opinions. The steps of the entropy method with sine trigonometric Pythagorean fuzzy entropy numbers are as follows (Ma et al. 2023). First, expert opinions were obtained based on the values listed in Table 1. Subsequently, these opinions are converted into sine trigonometric Pythagorean fuzzy sets.

By taking the average of k expert opinions, a fuzzy decision matrix ($A$) is formed, as shown in Eq. (1). In this context, $\mu$ is the membership value, while $v$ is the non-membership value. Equation (2) is used to calculate arithmetic means.

$$A = \begin{bmatrix} \left(\sin\left(\frac{\pi}{2}\mu_{11}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{11}^2}\right)}\right) & \cdots & \left(\sin\left(\frac{\pi}{2}\mu_{1n}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{1n}^2}\right)}\right) \\ \vdots & \ddots & \vdots \\ \left(\sin\left(\frac{\pi}{2}\mu_{m1}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{m1}^2}\right)}\right) & \cdots & \left(\sin\left(\frac{\pi}{2}\mu_{mn}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{mn}^2}\right)}\right) \end{bmatrix} \tag{1}$$

$$STPFWA = \left(\sqrt{1-\prod_{i=1}^{n}\left(1-\sin^2\left(\frac{\pi}{2}\mu_i\right)\right)^{1/k}}, \prod_{i=1}^{n}\left(\sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_i^2}\right)}\right)^{1/k}\right) \tag{2}$$

Matrix $A$ is then normalized. A normalized matrix ($R$) is created using Eq. (3).

**Table 1** Linguistic variables

| Linguistic term | Abb | Score | Pythagorean fuzzy sets | | Sine trigonometric pythagorean fuzzy sets | |
|---|---|---|---|---|---|---|
| | | | **μ** | **v** | **μ** | **v** |
| Very low | VL | 1 | 0.15 | 0.85 | 0.2334 | 0.5136 |
| Low | L | 2 | 0.25 | 0.75 | 0.3827 | 0.3716 |
| Moderately low | ML | 3 | 0.35 | 0.65 | 0.5225 | 0.2651 |
| Medium | M | 4 | 0.5 | 0.45 | 0.7071 | 0.1187 |
| Moderately high | MH | 5 | 0.65 | 0.35 | 0.8526 | 0.0702 |
| High | H | 6 | 0.75 | 0.25 | 0.9239 | 0.0353 |
| Very high | VH | 7 | 0.85 | 0.15 | 0.9724 | 0.0126 |

$$r_{ij} = \begin{cases} \left(\sin\left(\frac{\pi}{2}\mu_{ij}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{ij}^2}\right)}\right) \text{ for benefit criteria} \\ \left(\sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{ij}^2}\right)}, \sin\left(\frac{\pi}{2}\mu_{ij}\right)\right) \text{ for cost criteria} \end{cases} \tag{3}$$

The entropy value ($E$) of each criterion is calculated with Eq. (4).

$$E_j = \frac{1}{\left(\sqrt{2}-1\right)m}\sum_{i=1}^{m}\left(\sin\left(\frac{\pi}{4}\left(1+\mu_{ij}^2-v_{ij}^2\right)\right)+\sin\left(\frac{\pi}{4}\left(1-\mu_{ij}^2+v_{ij}^2\right)\right)-1\right) \tag{4}$$

In this process, $\frac{1}{\left(\sqrt{2}-1\right)m}$ is constant to keep the E value in the [0,1] range. Finally, the weights ($w$) are calculated using Eq. (5).

$$w_j = \frac{1-E_j}{n-\sum_{j=1}^{n}E_j} \tag{5}$$

**STPYF CRITIC**

The CRITIC method is a criteria weighting method. The basis of this method is the relationship between the criteria and the calculation of the standard deviation values of these items. The steps of the CRITIC method with sine trigonometric Pythagorean fuzzy numbers are as follows (Zhang and Wei 2023).

First, expert opinions were obtained based on the values listed in Table 1. Second, these opinions are converted into sinusoidal trigonometric Pythagorean fuzzy numbers. By taking the average of k expert opinions, a fuzzy decision matrix ($A$) is formed, as shown in Eq. (1). Here, $\mu$ is the membership value, while $v$ refers to the non-membership value. Equation (2) is used to calculate arithmetic means. Then, matrix $A$ is defuzzified by Eq. (6).

$$S(\sin p) = \sin^2\left(\frac{\pi}{2}\mu_p\right) - \left(\sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_p^2}\right)}\right)^2 \tag{6}$$

The defuzzified matrix of $A$ is normalized using Eq. (7). The normalized matrix ($B$) is given by Eq. (8).

$$b_{ij} = \begin{cases} \frac{x-min}{max-min} \text{ for benefit criteria} \\ \frac{max-x}{max-min} \text{ for cost criteria} \end{cases} \tag{7}$$

$$B = \begin{array}{c} \\ A1 \\ \vdots \\ Am \end{array} \begin{array}{c} \begin{array}{ccc} C1 & \ldots & Cn \end{array} \\ \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{bmatrix} \end{array} \tag{8}$$

The correlation matrix ($\rho$) is calculated by Eq. (9).

$$\widetilde{\rho}_{jk} = \sum_{i=1}^{m}\left(\widetilde{b}_{ij} - \widetilde{\overline{b}}_{j}\right)\left(\widetilde{b}_{ik} - \widetilde{\overline{b}}_{k}\right)/\sqrt{\sum_{i=1}^{m}\left(\widetilde{b}_{ij} - \widetilde{\overline{b}}_{j}\right)^{2}\sum_{i=1}^{m}\left(\widetilde{b}_{ik} - \widetilde{\overline{b}}_{k}\right)^{2}} \tag{9}$$

Equation (10) calculates the standard deviation ($\sigma$) of each criterion.

$$\widetilde{\sigma}_{j} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(\widetilde{b}_{ij} - \widetilde{\overline{b}}_{j}\right)^{2}} i = 1,2,\ldots,m \tag{10}$$

$C$ index values are calculated with Eq. (11).

$$\widetilde{C}_{j} = \widetilde{\sigma}_{j}\sum_{k=1}^{n}(1 - \widetilde{\rho}_{jk}) j = 1,2,\ldots,n \tag{11}$$

Finally, the weights ($w$) are identified using Eq. (12).

$$\widetilde{w}_{j} = \frac{\widetilde{C}_{j}}{\sum_{j=1}^{n}\widetilde{C}_{j}} \tag{12}$$

**STPYF RATGOS**

The present study is the first to propose the RATGOS multi-criteria ranking method for decision-making in the pension investment context. The basis of RATGOS is the similarity ratio of the alternatives to their optimal values. In the literature on multi-criteria decision-making methods, the RATGOS method as a current ranking method. The basis of this method is the calculation of the weighted geometric mean of the similarity ratios of alternatives to the optimal value based on a criterion. In the first stage of the method, optimal values were determined. For the benefit criterion, the highest column value was accepted as the optimal value, whereas for the cost criterion, the lowest value was accepted as the optimal value. These values are the similarity ratios of the alternatives to the optimal value and express how similar they are to the solution. In other words, the higher the ratio, the more likely is the most appropriate solution for that criterion. Criterion-based ratios are obtained by multiplying the weights of the criteria to obtain the weighted similarity ratio. The aim is to include the importance levels of the criteria in the process of determining the most suitable alternative. Based on these ratios, the similarities between the alternative and optimal values are averaged. Thus, if an alternative that is low in one criterion is good in another, the most accurate representative value is obtained by taking the average. At this stage, the geometric mean is preferred for measuring the central tendency. This is because the considered values are proportional. Although the arithmetic means of the two alternatives were the same, their geometric means were different. While the first alternative is high for only one criterion, the second alternative similarity ratio is 0.5, compared to the optimal value for the two criteria. The results of RATGOS also indicate that this alternative is more suitable (Oflaz et al. 2023).

The steps of the RATGOS method with sine trigonometric Pythagorean fuzzy numbers are as follows (Dinçer et al. 2023). First, the expert opinions were converted into sinusoidal trigonometric Pythagorean fuzzy numbers. Subsequently, the average of the expert opinions was obtained using Eq. (2). Thus, fuzzy decision matrix ($A$) can be obtained. Equation (6) is used to compute the defuzzified values in $A$ matrix. The optimal values for each criterion in matrix $A$ are determined using Eqs. (13) and (14).

$$optimal = \max a_i \, for\ benefit\ criteria \tag{13}$$

$$optimal = \max \frac{1}{a_i} for\ cost\ criteria \tag{14}$$

The factors are divided by the optimal result using Eqs. (15) and (16). Therefore, a normalization ($N$) procedure is applied.

$$N = \frac{A}{optimal} forbenefitcriteria \tag{15}$$

$$N = \frac{optimal}{A} forcostcriteria \tag{16}$$

A weighted normalization matrix ($Z$) is constructed using Eq. (17): Within this framework, $w$ defines the weights.

$$Z = wN \tag{17}$$

Based on the geometric mean ($G$), the average similarity ratio can be computed using Eq. (18).

$$G_i = \sqrt{\prod_{i=1}^{n}(1 + z_{ij})} - 1 \tag{18}$$

**STPYF TOPSIS**

The TOPSIS method is a multi-criteria decision-making method used for ranking alternatives. The basis of the method is to calculate the ideal distance of negative and positive values of the alternatives. The steps of the TOPSIS method with sine trigonometric Pythagorean fuzzy numbers are given below (Erdebilli et al. 2023).

Matrix $A$ in Eq. (2) is multiplied by the criterion weights. Thus, a weighted decision matrix ($H$) is obtained. Equation (19) is used for this purpose.

$$\lambda \text{sin} p_1 = \left( \sqrt{1 - \left(1 - \sin^2\left(\frac{\pi}{2}\mu_1\right)\right)^{\lambda}}, \left(\sqrt{1 - \sin^2\left(\frac{\pi}{2}\sqrt{1 - \nu_1^2}\right)}\right)^{\lambda} \right) \tag{19}$$

In the H matrix, the ideal positive ($V^+$) and ideal negative values ($V^-$) are calculated for each criterion. In this process, the score values in Eq. (6) are compared. Equations (20) and (21) were used as the benefit criteria, whereas Eqs. (22) and (23) are considered as the cost criteria.

$$V^- = \left\{ \nu_i | \min(S(h_i)) \right\} \tag{20}$$

$$V^{+} = \left\{ v_i | \max(S(h_i)) \right\} \tag{21}$$

$$V^{-} = \left\{ v_i | \max(S(h_i)) \right\} \tag{22}$$

$$V^{+} = \left\{ v_i | \min(S(h_i)) \right\} \tag{23}$$

Using Eqs. (24)–(27), the distances of each alternative from the ideal negative ($S^{-}$) and ideal positive ($S^{*}$) are calculated.

$$D(\sin p_1, \sin p_2) = 1 - \frac{1}{n} \sum_{i=1}^{n} \sin\left(\frac{\pi}{2} - \frac{\pi}{6}\left(\left|\mu_1^2 - \mu_2^2\right| + \left|v_1^2 - v_2^2\right| + \left|d_1^2 - d_2^2\right|\right)\right) \tag{24}$$

$$d = \sqrt{1 - \mu^2 - v^2} \tag{25}$$

$$S^{-} = D\left(H, V^{-}\right) \tag{26}$$

$$S^{*} = D\left(H, V^{+}\right) \tag{27}$$

The relative closeness coefficient to the ideal solution (***C***) is calculated with Eq. (28).

$$C = \frac{S^{-}}{S^{-} + S^{*}} \tag{28}$$

## Analysis results

In this study, a novel fuzzy decision-making model is developed. Figure 1 illustrates the details of the model.

The results of the proposed models and their comparison are presented in the following subsections.

### Definition of criteria and alternatives

After reviewing the literature, five indicators were defined for renewable energy investment decisions using pension funds. These factors are listed in Table 2.

Correct risk management is important for the effective use of retirement funds for renewable energy investments. Renewable energy projects are often sensitive to fluctuations in the energy market (Yang and Dodge 2024). Therefore, risks must be determined correctly and necessary precautions must be taken. Effective risk management enables more accurate measures to mitigate market volatility (Xu et al. 2024). The possibility of high returns should be considered when integrating pension funds into renewable energy investments. With high returns, it is possible to ensure the long-term sustainability of retirement funds (Miralles-Quirós and Miralles-Quirós 2024). By contrast, higher returns may increase participants' confidence in their retirement funds. This allows funds to be used more successfully (Ustaoglu 2024). Government incentives contribute to the effective transfer of retirement funds to renewable energy investments. These incentives reduce the costs of renewable energy projects (Imran et al. 2024). Government

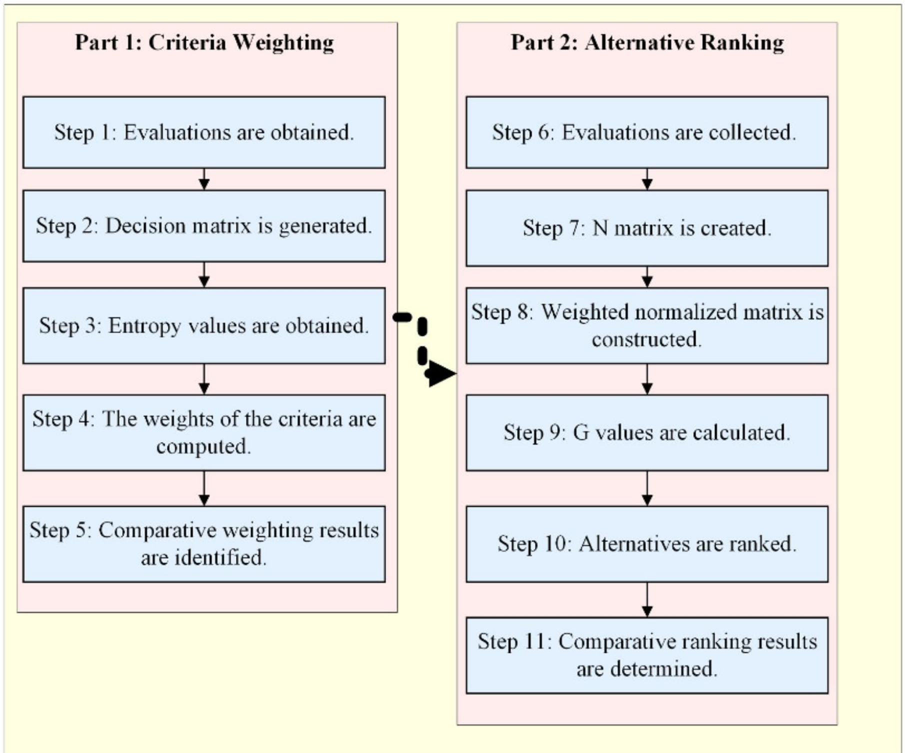



**Fig. 1** Proposed model details

**Table 2** List of indicators

| Indicators | Codes |
|---|---|
| Effective risk management | Risk |
| High return possibility | Return |
| Sufficient incentives and subsidies | Incentives |
| Effective regulatory compliance | Regulatory |
| Complexity of the process | Complexity |

incentives can reduce the uncertainties in project financing and operational processes (Xiaobao et al. 2024). Regulations are also important for the effective use of retirement funds in renewable energy investments. These regulations contribute to the formation of regulations in the energy sector (Jiang et al. 2024). A stable regulatory environment provides predictability for pension funds (Shu et al. 2024). This facilitates the planning of long-term investments. The complexity of these processes also negatively affects the effective transfer of pension funds to renewable energy investments (Kaya et al. 2024). Complex processes can delay investment decision-making. These delays may result in potential opportunities being missed (Baydaş et al. 2024). This situation significantly reduces the competitive advantage of a business. Additionally, the five renewable energy investment alternatives are listed in Table 3.

**Table 3** Renewable energy investment alternatives

| Name |
|---|
| Direct investment in clean energy |
| Clean energy funds |
| Yieldcos |
| Green bonds |
| Sustainable infrastructure |

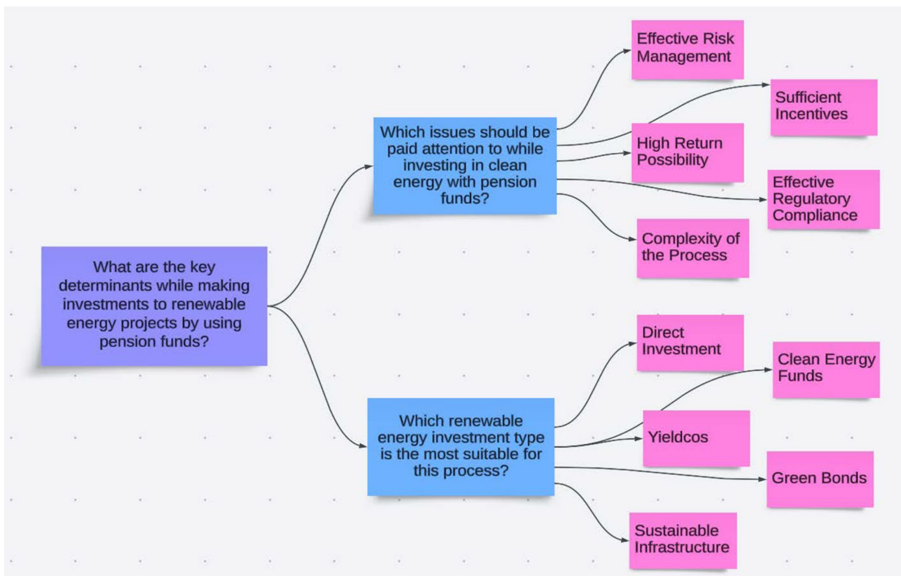



**Fig. 2** Conceptual framework

Direct clean energy investments can play an important role in adapting pension funds to renewable energy projects. Clean energy projects offer sustainable returns. This situation provides investors with significant confidence (Qiu et al. 2024). However, clean energy projects provide effective risk management for pension funds that seek to diversify their portfolios. Clean energy funds can play an important role in adapting pension funds to renewable energy projects (Fan et al. 2024). Teams that specialize in the sector typically manage clean energy funds. Pension funds can make better investment decisions using clean energy funds. Yieldcos can also be considered in the process of adapting pension funds for renewable energy projects (Kandpal et al. 2024). Yieldcos focus on long-term fixed-income projects. This ensures safer cash flow in retirement funds. Green bonds are another investment tool that can also be used in this process. Green bonds are often used to encourage investments in environmentally friendly projects. These products make it possible to invest in sustainable assets (Yiming et al. 2024). This supports businesses in implementing environment-friendly policies. Sustainable infrastructure can play an important role in adapting pension funds to renewable energy projects. Sustainable infrastructure projects generally have the potential for long-term stable returns (Mahmood et al. 2024). This provides pension funds with a significant competitive advantage. A graphical representation of the conceptual framework is shown in Fig. 2.

### Expert evaluations and decision matrix construction

In this process, an expert team was formed with three people. Most decision-making models consider the evaluations of three experts are taken into consideration (Kou et al. 2023a, b, c). The first expert is a professor of finance. He has numerous significant publications on pension funds and green energy finance. The other two are chief finance officers at international companies. They led many projects on investment decisions by pension funds. Evaluations were conducted by considering seven different scales according to these decision makers. The evaluation results are presented in Table 4.

In the process of obtaining expert opinions, each investment alternative is evaluated at all criteria levels using the linguistic expressions in Table 1. In alternative criterion matching, experts match their opinions with linguistic terms using the created digital form. The results of the pairings are summarized in Table 4. The expert opinions were converted into the STPFYs in Table 1 and averaged using Eq. (2): Table 5 lists the decision matrices.

### Weighting the criteria with sine trigonometric pythagorean fuzzy entropy

In the first stage of analysis, the criteria were weighted. Therefore, the average of the expert opinions was normalized using Eq. (3). All the criteria considered in this

**Table 4** Expert evaluations

| **Expert 1** | | | | | |
|---|---|---|---|---|---|
| | **Risk** | **Return** | **Incentives** | **Regulatory** | **Complexity** |
| Direct investment | VH | ML | L | VL | L |
| Clean energy funds | H | L | ML | VL | VL |
| Yieldcos | MH | L | VL | VL | ML |
| Green bonds | VH | MH | MH | H | MH |
| Sustainable infrastructure | H | VL | VL | L | L |
| **Expert 2** | | | | | |
| | **Risk** | **Return** | **Incentives** | **Regulatory** | **Complexity** |
| Direct investment | VH | L | L | L | ML |
| Clean energy funds | VH | ML | L | VL | L |
| Yieldcos | H | VL | L | VL | L |
| Green bonds | VH | H | H | MH | MH |
| Sustainable infrastructure | H | VL | L | VL | VL |
| **Expert 3** | | | | | |
| | **Risk** | **Return** | **Incentives** | **Regulatory** | **Complexity** |
| Direct investment | H | ML | VL | VL | L |
| Clean energy funds | VH | L | VL | L | VL |
| Yieldcos | H | L | L | L | VL |
| Green bonds | VH | MH | H | H | H |
| Sustainable infrastructure | H | ML | L | L | VL |

**Table 5** Decision matrix

| | Risk | | Return | | Incentives | | Regulatory | | Complexity | |
|---|---|---|---|---|---|---|---|---|---|---|
| Direct investment | 0.9614 | 0.0177 | 0.4828 | 0.2967 | 0.3418 | 0.4140 | 0.2936 | 0.4611 | 0.4369 | 0.3320 |
| Clean energy funds | 0.9614 | 0.0177 | 0.4369 | 0.3320 | 0.4035 | 0.3699 | 0.2936 | 0.4611 | 0.2936 | 0.4611 |
| Yieldcos | 0.9054 | 0.0444 | 0.3418 | 0.4140 | 0.3418 | 0.4140 | 0.2936 | 0.4611 | 0.4035 | 0.3699 |
| Green bonds | 0.9724 | 0.0126 | 0.8821 | 0.0558 | 0.9054 | 0.0444 | 0.9054 | 0.0444 | 0.8821 | 0.0558 |
| Sustainable infrastructure | 0.9239 | 0.0353 | 0.3658 | 0.4120 | 0.3418 | 0.4140 | 0.3418 | 0.4140 | 0.2936 | 0.4611 |

**Table 6** Entropy values and weights

| Criteria | E | W | Rank |
|---|---|---|---|
| Risk | 0.1928 | 0.5969 | 1 |
| Return | 0.8707 | 0.0956 | 5 |
| Incentives | 0.8619 | 0.1021 | 3 |
| Regulatory | 0.8532 | 0.1085 | 2 |
| Complexity | 0.8691 | 0.0968 | 4 |

study are beneficial. The entropy values ($E$) are then calculated using Eq. (4). The criteria weights are calculated using Eq. (5). The entropy values and weights are listed in Table 6.

Table 6 indicates that the most important criterion is risk minimization, with the greatest weight (0.5969). Effective regulations are another important issue. Complexity and returns are less important than others when making investment decisions to renewable energy projects using pension funds. Risk is the most important criterion affecting the utilization of pension funds for clean energy investments. Many risks can be mentioned in investments in this field. Clean energy projects require advanced technologies (Zhang et al. 2023a, b) and the personnel qualified to use these technologies (Yüksel et al. 2023). Additionally, income from clean energy projects may vary according to seasonal fluctuations (Li et al. 2023). In addition, the payback period for clean energy investments can be long (Silva Neves et al. 2023). Pension funds are financial instruments designed to provide financial security to individuals during retirement (Chen et al. 2023). Another important issue affecting the utilization of pension funds in clean energy projects is their complexity. Although clean energy projects are important for sustainability, they have many complexities. Clean energy projects face technical challenges such as advanced technology and integration (Li et al. 2023). Moreover, high initial investment costs and existing legal factors can increase this complexity (Herenčić et al. 2023). Risk management plays the most critical role in proper retirement fund management. Therefore, specific policies should be implemented. In this context, pension fund risks should be reviewed regularly. Therefore, a comprehensive evaluation should be conducted by applying different scenarios. However, technological investments must be increased to support the development of this process. Detailed data analysis can be performed, particularly with the application of new technologies. This allows for a more accurate risk prediction.

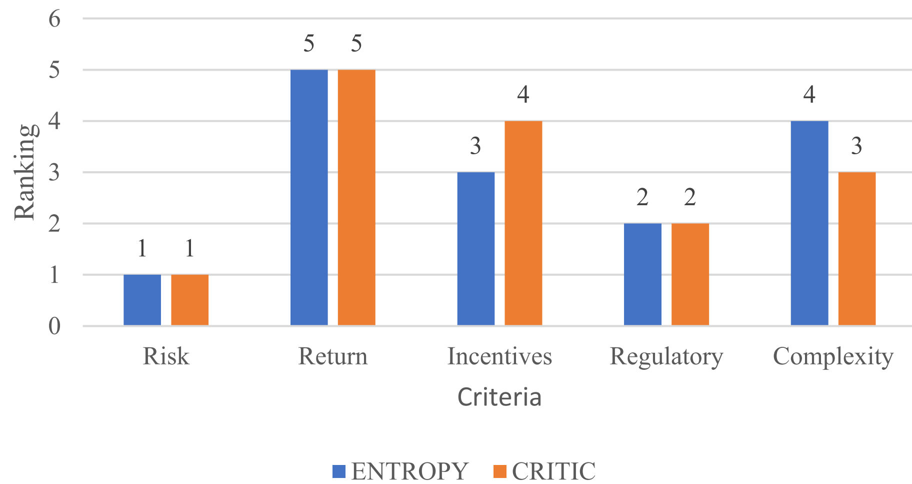



**Fig. 3** Criteria weighting comparison

**Table 7** Matrix N

| | Risk | Return | Incentives | Regulatory | Complexity |
|---|---|---|---|---|---|
| Direct investment | 0.9538 | − 0.6463 | − 0.9057 | − 1.0061 | − 0.7783 |
| Clean energy funds | 0.9538 | − 0.7783 | − 0.7722 | − 1.0061 | − 1.1394 |
| Yieldcos | 0.7325 | − 1.0256 | − 0.9057 | − 1.0061 | − 0.8745 |
| Green bonds | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Sustainable infrastructure | 0.8031 | − 0.9778 | − 0.9057 | − 0.9057 | − 1.1394 |

### Comparison of the weighting results with the sine trigonometric pythagorean fuzzy CRITIC

The weights obtained using the STPFY-entropy method were compared to those computed using the STPFY-CRITIC method. For this purpose, the decision matrix shown in Table 3 is considered. The criteria weights are calculated using Eqs. (6)–(12). The comparative weighting results are shown in Fig. 3.

According to the comparison, the most and least important factors were similar. The results of both methods indicate that risk is the most important criterion and return is the least important indicator in this framework. This provides information on the coherence of the findings.

### Ranking the investment alternatives with sine trigonometric pythagorean fuzzy RATGOS

In the second stage, the clean energy investment alternatives are ranked using the sine trigonometric Pythagorean fuzzy RATGOS method. The results are then compared with those of the sine trigonometric Pythagorean fuzzy TOPSIS method. The values in Table 5 are defuzzified using Eq. (6). For example, the difference between the squares of the two components of the first element of the matrix is considered. The other elements of the matrix were obtained in a similar manner. The optimal values of each column are then determined using Eqs. (13) and (14). Matrix N is calculated using Eqs. (15) and (16). The first value is equal to the result of (0.851/0.892). Matrix *N* is presented in Table 7.

**Table 8** Weighted normalized matrix

| | Risk | Return | Incentives | Regulatory | Complexity |
|---|---|---|---|---|---|
| Direct investment | 0.5693 | − 0.0618 | − 0.0925 | − 0.1092 | − 0.0753 |
| Clean energy funds | 0.5693 | − 0.0744 | − 0.0788 | − 0.1092 | − 0.1103 |
| Yieldcos | 0.4373 | − 0.0981 | − 0.0925 | − 0.1092 | − 0.0846 |
| Green bonds | 0.5969 | 0.0956 | 0.1021 | 0.1085 | 0.0968 |
| Sustainable infrastructure | 0.4794 | − 0.0935 | − 0.0925 | − 0.0983 | − 0.1103 |

**Table 9** G values and ranking results

| Alternatives | G values | Ranking results |
|---|---|---|
| Direct Investment | 0.1218 | 5 |
| Clean Energy Funds | 0.1321 | 3 |
| Yieldcos | 0.1297 | 4 |
| Green Bonds | 0.1437 | 1 |
| Sustainable Infrastructure | 0.1351 | 2 |

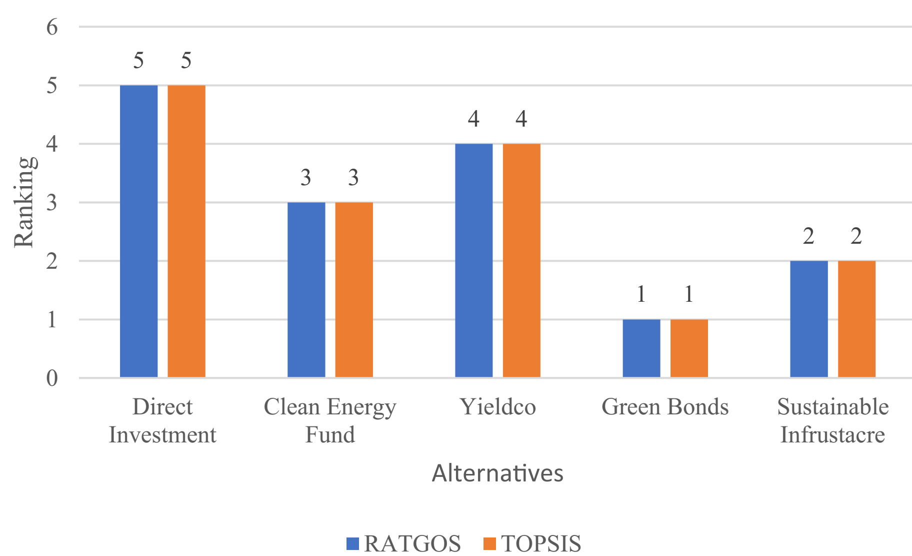



**Fig. 4** Comparison of alternative ranking methods

The weighted normalized matrix was obtained using Eq. (17). Within this scope, the weights obtained using the sine trigonometric Pythagorean fuzzy entropy method are considered. The weighted normalized matrix is presented in Table 8.

The *G* values are then calculated using Eq. (18). The *G* values and rankings of the alternatives are listed in Table 9.

Table 9 demonstrates that the most suitable alternative is green bonds because they have the greatest G value. However, Yieldcos and direct investments rank last.

**Comparison of the results with the sine trigonometric pythagorean fuzzy TOPSIS**

The ranks obtained using the sine trigonometric Pythagorean fuzzy RATGOS method are compared with those computed using the sine trigonometric Pythagorean fuzzy TOPSIS method. In this context, the decision matrix presented in Table 5 is used. The alternative ranks are calculated using Eqs. (19)–(28). The comparative results are depicted in Fig. 4.

According to the comparison, the results of the two methods were similar. Thus, the proposed model generates coherent and reliable results. Therefore, it is important to invest in clean energy projects. This study identifies several important factors affecting the utilization of pension funds in clean energy investments. However, green bonds should be prioritized for the effective use of pension funds for clean energy investments. Green bonds are available to finance environmentally friendly and sustainable projects (Feng et al. 2023). In addition, greenbond investors receive emotional satisfaction from supporting environment-friendly projects. Wang et al. (2023) determined that the use of green bonds increased the use of wind and hydroenergy in OECD countries. Zhang and Umair (2023) found significant dynamic spillover effects between green bonds and renewable energy stocks. Green bonds have been identified as an important alternative for sustainable investments and risk management of pension funds. In this context, we present policy recommendations for the proper management of pension funds using green bonds. In this context, the awareness of the benefits of green bonds must increase. For this purpose, training should be organized for the public. Similarly, standards for green bonds must be established. Based on these standards, the efficiency of the process can be increased. Government incentives and tax reductions are vital for this process. These incentives can help in the development of green bonds, as they contribute to reducing costs.

When comparing the results of the RATGOS and TOPSIS methods, the weights of the CRITIC and Entropy methods were considered separately. In other words, the

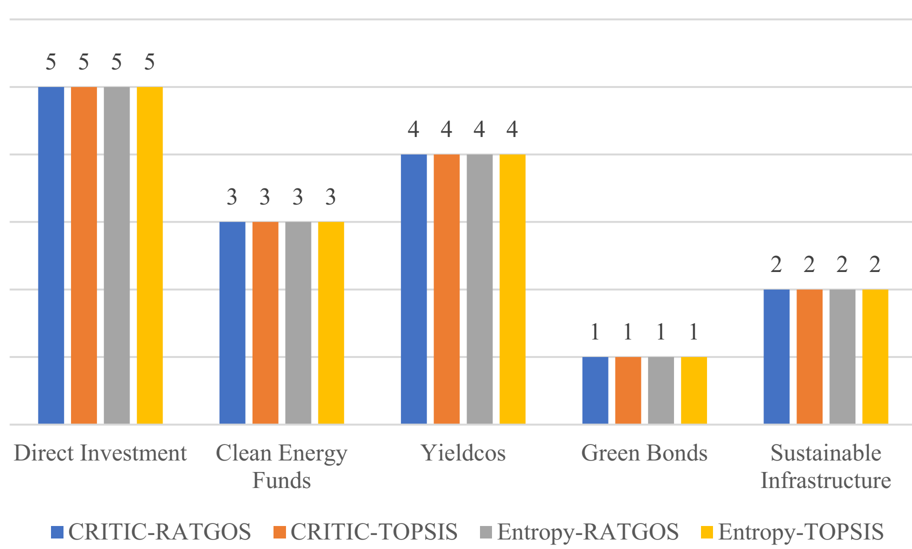



**Fig. 5** Comparative analysis

analyses are repeated using a combination of weighting and ranking methods. The results are shown in Fig. 5. The results obtained are similar.

### Sensitivity analysis

In addition to comparing the results of the two methods, a sensitivity analysis was performed to ensure consistency. At this stage, the effects of small changes in the criteria weights on the alternatives is examined. Based on the weights listed in Table 6, new weights are obtained via simulation. The values obtained for entropy are used as the average of the weights in the simulation. New rankings are obtained by repeating the RATGOS steps with new weights. Unlike the weights in the first stage of the study, 10 different situations are considered, and the alternatives are ranked. The results of the RATGOS method for ten different scenarios are presented in Fig. 6.

Figure 6 indicates no change in the ranking of the alternatives according to the different weights. That is, minimal changes in the criterion weights do not affect the order of the investment alternatives. According to the sensitivity analysis, the priority of investment alternatives is consistent.

## Discussion and policy implications

According to the weighting results, the risk factors are important for these investments, which are discussed in the literature. For example, Wang and Chang (2023) stated that risk factors affect clean energy investment. Alsagr (2023) identified that financial risk should be reduced to increase investments in this field. Abbas et al. (2023) stated that risk should be minimized for further investment in renewable resources. Zhang et al. (2023a, b) conclude that seasonal risks affect clean energy investments. Merrifield and Fowler (2023) and Saqib and Dincă (2023) emphasized the importance of legal regulations and government support in clean energy investments. Market fluctuations and political uncertainties further complicate these investments (Ahmed et al. 2023). Several studies highlighted the importance of this issue. For example, Abou Houran and Mehmood (2023) mentioned that the complexity of investments negatively affects performance. Fang (2023) emphasized that the complexity of investments has a negative impact on investment. Belaïd et al. (2023) found that complex situations affect investments. Hong et al. (2023) found that the return on investment is an important criterion affecting energy investment processes.

Green bonds are the best investment alternative for transferring retirement funds to clean energy projects. In this context, countries can implement measures to popularize and

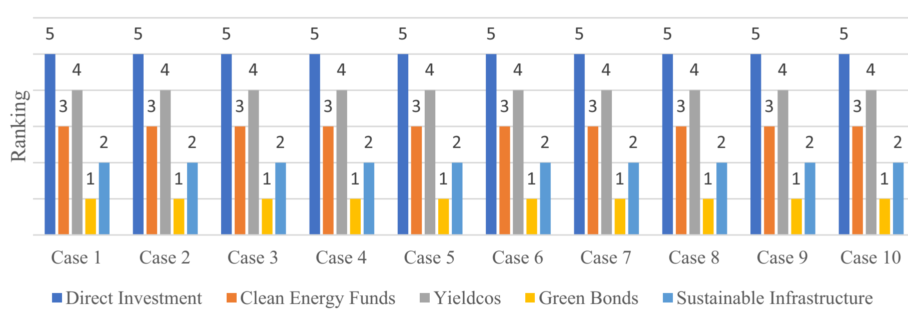



**Fig. 6** Sensitivity analysis results

increase their green bonds. In this context, green bond standards must first be determined. Green bonds issued in accordance with these standards can attract investors' attention. On the other hand, effective campaigns should be organized to promote green bonds to investors. This contributes to a significant increase in the demand for green bonds. In addition, government support for increasing green bonds is of great importance. In this context, tax reductions can significantly increase issuances of these bonds. Moreover, institutions issuing green bonds should inform investors about environment-friendly projects. Thus, investors can better understand the positive environmental effects of these projects, which can facilitate the development of green bonds.

## Conclusion

This study conducts a priority analysis of the determinants of investing in renewable energy projects using pension funds. This study constructs a novel fuzzy decision-making model. First, five indicators for this process are weighted using an entropy methodology based on sine trigonometric Pythagorean fuzzy sets. The CRITIC methodology is also considered to make a comparative evaluation. Second, five different clean energy investment alternatives for pension funds are ranked using the RATGOS methodology. Similarly, this analysis was performed by considering the TOPSIS technique to check the reliability of the ranking results. The most important criterion is risk minimization, which has the greatest weight. Effective regulations are another significant issue. According to the comparison results with the sine trigonometric Pythagorean fuzzy CRITIC, the results of the two methods are similar. Furthermore, the ranking results indicate that the most suitable renewable energy alternative is green bonds. A comparison with the sine trigonometric Pythagorean fuzzy TOPSIS show that the proposed model generates coherent and reliable results.

The novelty of this study is that it presents more significant indicators for renewable energy investment decisions by pension funds. Therefore, this study's findings pave the way for investors to make investment decisions under these circumstances. Furthermore, the main methodological contribution of this study is the proposal of the RATGOS technique as a multi-criteria decision-making model. To overcome the criticisms of similar ranking techniques, the RATGOS methodology is created while considering the geometric mean in the analysis process. In this study, only pension funds were considered in renewable energy investment decisions. This situation can be considered the main limitation of this evaluation. Different financial instruments can be considered in subsequent studies. On the other hand, the proposed model has some limitations. For instance, the weights of the different experts were assumed to be equal. However, the qualifications of these individuals may differ according to demographic factors. Therefore, in future studies, a novel model should be constructed to calculate the significance weights of experts according to their classifications. This situation facilitates more effective evaluations. Additionally, the CRITIC technique was used to weigh the criteria. However, the main limitation of this technique is that the causal directions among the indicators cannot be considered. Thus, for future evaluations, the M-SWARA or DEMATEL techniques can be used to generate an impact relation map of the items.

## Appendix

See Table 10.

**Table 10** Literature review results

| Studies | Main conclusion |
|---|---|
| Gutierrez et al. (2019) | the funds' risk-return profile plays a key role while making investments by using pension funds |
| Kul et al. (2020) | |
| Martí-Ballester (2020) | |
| Sendstad et al. (2022) | |
| Peksevim and Ercan (2023) | |
| Sun et al. (2023) | Compliance with legal regulations is one of the investors' most important evaluation criteria |
| Fiori Maccioni (2023) | |
| Defau and De Moor (2021) | |
| Taghizadeh-Hesary and Yoshino (2020) | Investing in clean energy presents opportunities for pension funds to diversify their assets and generate long-term returns |
| Binkley et al. (2020) | |
| Sartzetakis (2021) | |
| Polzin and Sanders (2020) | |
| Seran et al. (2023) | |
| Sangiorgi and Schopohl (2021) | |
| Mastrogiacomo et al. (2023) | Sustainable infrastructure investments allow pension funds to diversify their clean energy investment portfolios |
| Sengupta et al. (2018) | |
| Fragnière et al. (2023) | |
| Andersen and Dreyer (2023) | |

**Abbreviations**

CRITIC Criteria Importance Through Intercriteria Correlation
RATGOS Ranking Technique by Geometric Mean of Similarity Ratio to Optimal Solution
TOPSIS Technique for Order Preference by Similarity to Ideal Solution

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**Author contributions**

SY participated in the design of the study, performed the statistical analysis and helped to draft the manuscript. SE participated in the design of the study and performed the statistical analysis. HD participated in the design of the study and performed the statistical analysis. HM conceived of the study and participated in its design and coordination and helped to draft the manuscript. MU conceived of the study and participated in its design and coordination and helped to draft the manuscript. YG conceived of the study and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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**Competing interests**

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