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PERFORMANCE EVALUATION OF SUSTAINABLE ENERGY ALTERNATIVES TO OBTAIN EFFICIENT HYBRID ENERGY INVESTMENTS

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Abstract. This study evaluates the synergy of coalition for hybrid renewable energy (RWB) system alternatives. In this context, the alternative sources of hybrid RWB system are examined to illustrate the impact-relation directions among them with multi SWARA based on q-ROFs and golden cut. Next, the performances of renewable alternatives are measured in terms of the synergy of coalition with game theory and Shapley value. It is concluded that solar energy is the most suitable RWB alternative for synergy to increase efficiency in investments. However, biomass does not have a significant influence on providing synergy in energy investments. Therefore, solar energy should be prioritized for hybrid energy investments. Especially with the effect of technological developments, the efficiency of solar energy investments increases significantly. Thus, solar energy investments have become quite suitable for increasing the synergy in hybrid energy projects. Furthermore, necessary research should be conducted to make biomass energy more efficient.

Keywords: hybrid energy, renewable energy, energy investments, SWARA, q-ROFs, Shapley value.

JEL Classification: D81, Q42.

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1. Introduction

Hybrid energy investments are projects where different renewable energy sources are integrated and implemented. It is possible to talk about many different advantages of these investments. First, owing to these projects, it becomes easier to produce uninterrupted energy. In these projects, different types of renewable energies are brought together. This situation also helps to achieve balance in energy production. On the other hand, energy storage processes can also become more effective with the help of hybrid projects. This condition has a positive contribution to manage problems caused by fluctuations in energy demand more effectively (Nkwanyana et al., 2023). Moreover, hybrid energy projects also help increase energy production capacity. This situation contributes significantly to increasing energy revenues. Thus, it is possible to increase the financial performance of projects. In addition to this issue, hybrid energy projects also enable greater use of clean energy. This helps reduce environmental problems caused by energy production. Using fossil fuels in energy generation is accepted as the main reason of the carbon emission problem (Akarsu & Genç, 2022). Thus, renewable energy projects should be increased to overcome this problem. The main barrier for this situation is the high-cost problem of the renewable energy projects (Reveles-Miranda et al., 2024). Hence, with the help of hybrid energy investments, these problems can be solved in a more effective manner.

Choosing the appropriate renewable energy combination for hybrid energy projects is very important for the performance of the project. An incorrect combination may result in lower energy efficiency. This situation may negatively affect the financial performance of the project. Similarly, incorrect combination of renewable energy may prevent hybrid projects from producing uninterrupted energy (Miao et al., 2023). In this regard, an unbalanced combination can lead to interruptions in energy supply. On the other hand, creating this combination incorrectly can reduce cost effectiveness. As a result, the returns on investments decrease significantly. Furthermore, failure to integrate different energy sources harmoniously can lead to technical problems. In this process, operating costs increase because of the incompatibility of different technologies. Similarly, incorrectly creating the energy combination also causes negative environmental effects (Babatunde et al., 2022). In this context, if the selected renewable energy type is not suitable for the geography, it may negatively affect the ecosystem. The energy security problem is another factor that should be taken into consideration in this process (Zhang et al., 2024). Choosing the wrong energy combination can cause disruptions in the energy production process. In summary, there is a strong need for a new study to understand optimal renewable energy combinations for hybrid energy projects. However, in the literature, there are limited studies that focused on this situation.

Accordingly, this study aims to understand the optimal renewable energy combinations for the effectiveness of the hybrid energy projects. For this purpose, a novel fuzzy decision-making model is created with two different stages. First, the priorities and impact relation map are analyzed for the renewable energy system alternatives. In this framework, q-ROF M-SWARA methodology is taken into consideration. On the other side, the second stage includes assessing the synergy of coalition for hybrid renewable energy system alternatives in terms of the synergy of coalition by using the game theory and Shapley value respectively. The main motivation of this study is that a novel decision-making model should be generated to make appropriate evaluation for hybrid energy projects. Existing models in the literature are criticized because of some reasons. For instance, causal directions of the factors should be identified in addition to the calculation of the weights. However, in models where techniques such as AHP and ANP are used, the causal relationship between variables cannot be determined (Manirathinam et al., 2023; Yazdani et al., 2023). This situation helps to reach more effective findings. For this purpose, a new methodology, M-SWARA, is created in this study to understand the causal relationships.

The main contributions of this study are given below. (i) A novel decision-making model is proposed in this study to make assessment regarding the hybrid energy projects. In this model, game theory, Shapley value and fuzzy decision-making methodology are integrated. Therefore, this novel model makes a more sensitive evaluation for these projects. (ii) Creating M-SWARA methodology has also a significant contribution to the literature. Although classical SWARA methodology can compute the weights of the criteria, the causal directions of the factors cannot be identified with this technique. However, renewable energy alternatives may have an impact on the performance of each other. Thus, for the purpose of selecting effective combination of the renewable energy alternatives, causality relationship should be taken into consideration. For this situation, some extensions are implemented to the SWARA technique and M-SWARA approach is created. Thus, causal relationship between the items can be defined.

Literature review is conducted in the second part. Methodological information is given in the next part. Findings are underlined in the following section. Discussions and conclusions are explained in the final parts.

2. Literature review

Hybrid energy systems contribute significantly to increasing energy efficiency. The use of RWB helps to decrease carbon emissions. This situation also reduces the environmental pollution problem. Therefore, RWB generation is important for the solution of a very important problem (Qi et al., 2021). On the other hand, the installation cost of RWB alternatives is quite high. In addition, it may not be possible to produce a stable amount of energy from these types of energy (Dong et al., 2023). This leads to an increase in the costs of the projects. Thanks to properly designed hybrid energy systems, energy investments can become more efficient (Liu et al., 2021). Huang et al. (2021) focused on the design of hybrid energy projects. They defined that for the energy efficiency, hybrid energy projects should be encouraged. Guo et al. (2021) made an optimization regarding the hybrid energy systems. They claimed that cost management process can be implemented more appropriately for RWB investments when hybrid systems are taken into consideration. Zhang et al. (2021) examined the benefits of hybrid energy system for China. They identified that energy investments can become more efficient with the help of hybrid systems. Besides, Abba et al. (2022) and Adefarati et al. (2023) evaluated methods used in the literature for assessing and mitigating the risks of renewable energy investment for developed and developing countries.

Some scholars also examined the importance of technological investments for the performance of hybrid energy projects. Hybrid systems include more than two different RWB types. However, each alternative includes complex stages so that there is a strong need for using new technologies (Arent et al., 2021; He et al., 2022). The costs of these projects can be reduced by giving more importance to the technological development (Kumar & Karthikeyan, 2024). Additionally, technological developments also help to process to run effectively (Pang et al., 2021). Because of this issue, hybrid energy investors should have sufficient technological background (Wang et al., 2021; Ho et al., 2021). Otherwise, it becomes quite difficult to provide sustainability of these hybrid energy projects (Khosravi et al., 2021; Hoseinzadeh & Garcia, 2022). Peppas et al. (2021) made performance evaluation for hybrid energy projects. It is claimed that technological improvements play a critical role for this situation. Barelli et al. (2021) also highlighted the similar issues for the performance improvement of these projects. Kallio and Siroux (2022) and Wilberforce et al. (2023) revealed that hybridization amplified meaningly cost-free electricity production and eased the drop of biomass use and costly exergy destruction by evaluating thermo-economically a hybrid renewable energy system based on cogeneration from a biomass-fueled Stirling engine micro-CHP unit and photovoltaic-thermal collectors.

The relationship between hybrid energy projects and carbon emission was also studied by many researchers. Hybrid energy projects contain more than two different RWB alternatives so that clean energy systems can be improved (He et al., 2021). However, RWB alternatives have high costs so that investors do not prefer them (Güven & Mengi, 2023). Hybrid energy systems have a contribution to handle high-cost problem more effectively (Ross & Bindra, 2021). Owing to this situation, hybrid systems help to overcome carbon emission problem (Kamel et al., 2021; Qiu et al., 2023). Hills et al. (2021) examined hybrid energy systems with dynamic modelling and simulation technique. They concluded that effective hybrid systems have a decreasing impact on the carbon emission problem. Ali et al. (2021) evaluated hybrid energy systems in Pakistan and determined that there is a positive correlation between effective hybrid energy systems and carbon emission reduction. Aloini et al. (2021) suggested a methodology for optimum synthesis, design, and operation of the energy system for a case study of a farm hostel in Italy, involving a simulation engine and a multi-objective optimisation algorithm, with potential savings of up to 47 k€ and 320 tCO2. Guo et al. (2022) developed a fuzzy multi-criteria group decision making framework and detected 9 quantitative and 7 qualitative evaluation indicators for the investment decisions of power-photovoltaic-hydrogen storage projects. Jahangir et al. (2022) used the Hybrid Optimization Model for Electric Renewables (HOMER) Pro software to discover that an on-grid photovoltaic panel, bio, diesel, and battery system is the most cost-effective and carbon-saving option. Carbon capture and storage has been shown by Lee et al. (2022) to be reasonably sustainable and can support accomplish emission reduction targets if costs are lowered through technological innovation.

Hybrid energy design is another important topic in the literature. In this framework, many different RWB alternatives can be considered for the design of these systems (Nguyen et al., 2021; Karaaslan & Gezen, 2022). Each alternative can have some specific advantages and disadvantages (Gupta et al., 2021; Yazdani et al., 2023). Recent technological developments have a decreasing impact on the costs of solar energy projects. However, in the evening time, solar panels cannot generate energy (Bhattacharjee & Nandi, 2021; Alonso et al., 2023). Additionally, for the effectiveness of the wind energy, selected location plays an essential role. The performance of hydroelectric power plants is very low when there is a drought (Ren et al., 2022; Rezk et al., 2022). Hence, the design of the hybrid energy is very important for the performance improvement (Huang et al., 2021; El Mezdi et al., 2023). Turkdogan (2021) focused on the ways to improve the performance of the hybrid energy systems and defined that effective design plays a very crucial role for the achievement of this purpose.

Some important conclusions can be reached as a result of the literature review. For the purpose of performance improvements of the hybrid energy projects, appropriate renewable energy combinations can be generated. The main reason behind this situation is that incorrect combination may negatively affect the financial performance of the project. This condition also leads to interruptions in energy supply that can create some problems regarding cost management. Consequently, there is a strong need for a new study to understand optimal renewable energy combinations for hybrid energy projects. Nevertheless, the studies in the literature that focused on this issue are limited. Therefore, a comprehensive evaluation should be conducted to find answer for these questions. Fuzzy multi-criteria decision-making models were preferred by some scholars in the literature. For instance, Peirow et al. (2023) and Majumder et al. (2023) aimed to weight the indicators of the hybrid energy investment performance by using ANP methodology. In addition to these studies, Yazdani et al. (2023) and Manirathinam et al. (2023) also created a model with the help of AHP approach to understand the key performance indicators of hybrid energy projects. However, the main limitation of these studies is that causality analysis cannot be performed in these evaluations. The main determinants of the hybrid energy investments may have an influence on each other. Thus, a novel decision-making model should be generated to make appropriate evaluation for hybrid energy projects. To fill this missing part in the literature, a new methodology, M-SWARA, is created in this study to understand the causal relationships among the factors.

3. Methodology

Coalition game theory and Shapley value, q-ROFSs and SWARA are explained in this section.

3.1. Coalition game theory and shapley value

Game theory refers to the situation in which two or more players are involved in a strategy to achieve the desired outcome. Equations (1) and (2) demonstrate group and individual rationalities $\left(v(N),\ v(i)\right)$. N defines the number of players whereas x represents the reward vector (Alhasnawi et al., 2021):

$$v\left(N\right)=\sum_{i=1}^{i=n}x_i; \tag{1}$$

$$x_i \ge v\left(\left\{i\right\}\right). \tag{2}$$

Equation (3) demonstrates the imputation (y) that dominates x with a coalition S:

$$\sum\nolimits_{i\in S} y_i \le v\left(S\right),\ \ y_i > x_i. \tag{3}$$

Shapley value refers to the effects of the cooperation when the contributions the players are not equal (Smith & Alvarez, 2021). Equation (4) represents the details:

$$x_i = \sum_{\text{all } S \text{ for which } i \text{ is not in } S} \frac{\left|S\right|!\left(n-\left|S\right|-1\right)!}{n!}\left[v\left(S\cup\left\{i\right\}\right)-v\left(S\right)\right]. \tag{4}$$

3.2. q-ROFSs with golden cut

IFSs consider membership $\left(\mu_I(\vartheta)\right)$ and non-membership $\left(n_I(\vartheta)\right)$ degrees (MPP and NPP) to give better solutions for the complex problems. Equation (5) explains these sets (Atanassov, 1983):

$$I=\left\{\vartheta,\mu_I\left(\vartheta\right),n_I\left(\vartheta\right)/\ \vartheta\epsilon U\right\}. \tag{5}$$

Equation (6) includes the condition of IFSs:

$$0 \leq \mu_I(\vartheta) + n_I(\vartheta) \leq 1. \quad (6)$$

Yager (2013) generated PFSs with new grades (μ_P, n_P) as in Equation (7):

$$P = \{\vartheta, \mu_P(\vartheta), n_P(\vartheta) / \vartheta \epsilon U\}. \quad (7)$$

Equation (8) should be met in this regard:

$$0 \leq (\mu_P(\vartheta))^2 + (n_P(\vartheta))^2 \leq 1. \quad (8)$$

Yager (2016) introduces q-ROFSs by extending IFSs and PFSs with new degrees (μ_Q, n_Q) as in Equation (9):

$$Q = \{\vartheta, \mu_Q(\vartheta), n_Q(\vartheta) / \vartheta \epsilon U\}. \quad (9)$$

The condition of these sets is shown in Equation (10):

$$0 \leq (\mu_Q(\vartheta))^q + (n_Q(\vartheta))^q \leq 1,\ q \geq 1. \quad (10)$$

Equation (11) represents indeterminacy degree:

$$\pi_Q(\vartheta) = \left((\mu_Q(\vartheta))^q + (n_Q(\vartheta))^q - (\mu_Q(\vartheta))^q (n_Q(\vartheta))^q\right)^{1/q}. \quad (11)$$

Operations are indicated in Equations (12)–(16):

$$Q_1 = \{\vartheta, Q_1(\mu_{Q_1}(\vartheta), n_{Q_1}(\vartheta)) / \vartheta \epsilon U\}$$
$$\text{and } Q_2 = \{\vartheta, Q_2(\mu_{Q_2}(\vartheta), n_{Q_2}(\vartheta)) / \vartheta \epsilon U\}; \quad (12)$$

$$Q_1 \oplus Q_2 = \left(\left(\mu_{Q_1}^q + \mu_{Q_2}^q - \mu_{Q_1}^q \mu_{Q_2}^q\right)^{1/q}, n_{Q_1} n_{Q_2}\right); \quad (13)$$

$$Q_1 \otimes Q_2 = \left(\mu_{Q_1} \mu_{Q_2}, \left(n_{Q_1}^q + n_{Q_2}^q - n_{Q_1}^q n_{Q_2}^q\right)^{1/q}\right); \quad (14)$$

$$\lambda Q = \left(\left(1 - \left(1 - \mu_Q^q\right)^\lambda\right)^{1/q}, (n_Q)^\lambda\right), \lambda > 0; \quad (15)$$

$$Q^\lambda = \left((\mu_Q)^\lambda, \left(1 - \left(1 - n_Q^q\right)^\lambda\right)^{1/q}\right), \lambda > 0. \quad (16)$$

Equation (17) represents score function:

$$S(\vartheta) = (\mu_Q(\vartheta))^q - (n_Q(\vartheta))^q. \quad (17)$$

In this study, degrees are calculated with golden cut (φ) (Livio, 2008). Equation (18) gives information about this situation. In this context, large and small quantities are shown as *a* and *b*:

$$\varphi = \frac{a}{b} \text{ where, } a > b > 0. \quad (18)$$

Equation (19) includes he algebraic form:

$$\varphi = \frac{1+\sqrt{5}}{2} = 1.618\ldots. \quad (19)$$

Golden cut-based degrees are given in Equation (20):

$$\varphi = \frac{\mu_G}{n_G}. \quad (20)$$

Equations (21) and (22) demonstrate the integration of q-ROFSs with golden cut:

$$Q_G = \left\{\vartheta, \mu_{Q_G}\left(\vartheta\right), n_{Q_G}\left(\vartheta\right) / \vartheta \epsilon U\right\}; \quad (21)$$

$$0 \le \left(\mu_{Q_G}\left(\vartheta\right)\right)^q + \left(n_{Q_G}\left(\vartheta\right)\right)^q \le 1,\ q \ge 1. \quad (22)$$

3.3. M-SWARA with q-ROFSs

Keršuliene et al. (2010) introduced SWARA for the purpose of calculation of weights of the items and relation degrees. The matrix is developed with evaluations of the experts as in Equation (23):

$$Q_k = \begin{bmatrix} 0 & Q_{12} & \cdots & \cdots & Q_{1n} \\ Q_{21} & 0 & \cdots & \cdots & Q_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ Q_{n1} & Q_{n2} & \cdots & \cdots & 0 \end{bmatrix}. \quad (23)$$

Next, q-ROFSs and score function are constructed. Equations (24)–(26) are considered to compute the values of s_j (significance rate), k_j (coefficient), q_j (recalculated weight), and w_j (weights):

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases}; \quad (24)$$

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases}; \quad (25)$$

$$\text{If } s_{j-1} = s_j,\ q_{j-1} = q_j;\ \text{If } s_j = 0,\ k_{j-1} = k_j$$

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k}. \quad (26)$$

Stable values are defined while limiting and transposing the matrix with the power of $2t$ + 1. Finally, weights and relations degrees are computed.

4. Analysis

This paper aims to evaluate the synergy of coalition for hybrid RWB system alternatives. A new model is constructed by using coalition game theory, q-ROFSs and SWARA with golden cut. Figure 1 explains the steps of this model.

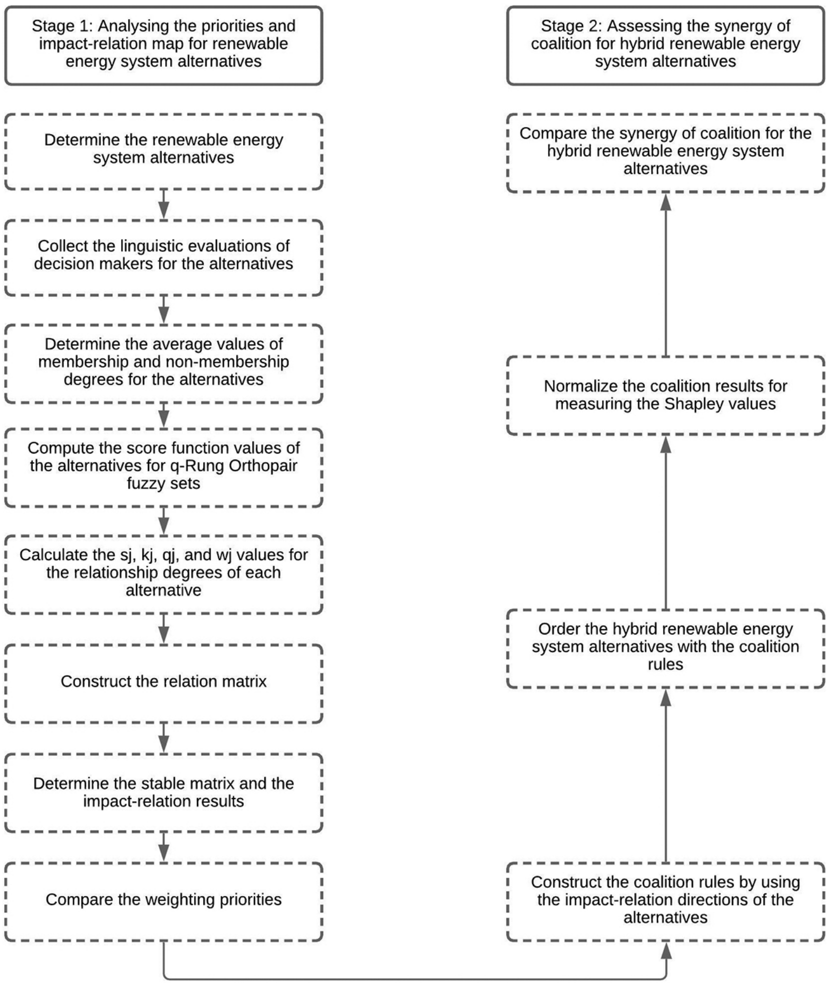

Figure 1. Steps of model

In this context, four RWB alternatives are selected to find optimum synergy of coalition in the investments as in Table 1.

Three decision makers, who have important experience in RWB investments, make evaluations. One of these decision makers is the academician. He has 25 years of working experience, and he has lots of publishments regarding energy efficiency, renewable energy projects and energy finance. Other two decision makers work as top managers in international renewable energy companies. They have worked in many different renewable energy generation projects. The scales and degrees in Table 2 are used for the conversion of these evaluations.

Evaluations are detailed in Table A1 in the Appendix part. Average values are shown in Table A2. Score functions are represented in Table A3. On the other side, Table A4 includes the critical values in the analysis process. Relation matrix is constructed in Table A5. Moreover, Table A6 indicates the stable matrix. Relationship between the alternatives is indicated in Figure 2.

Table 1. Alternatives

Alternatives	References
Biomass (BSS)	Bhuiyan et al. (2022)
Wind (WND)	Dong et al. (2022a, 2022b)
Hydro (HDR)	Bulut and Özcan (2021)
Solar (SOR)	Li et al. (2021)

Table 2. Degrees and scales

Scales	MPP	NPP
No (n)	0.40	0.25
some (s)	0.45	0.28
normal (m)	0.50	0.31
high (h)	0.55	0.34
very high (vh)	0.60	0.37

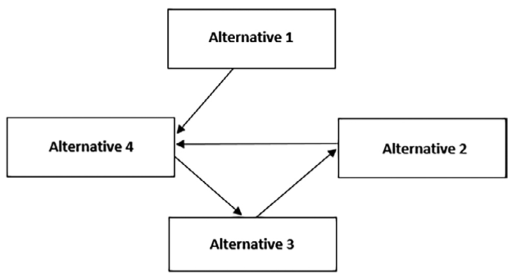

Figure 2. Impact-relation map

Biomass (alternative 1) and wind (alternative 2) have an impact on solar (alternative 4). Moreover, hydro (alternative 3) is influenced by solar (alternative 4). Furthermore, wind (alternative 2) is affected by hydro (alternative 3). Results are summarized in Table 3.

Solar (alternative 4) has the highest weight for all calculations. Additionally, hydro (alternative 3) is another crucial RWB type. Also, biomass (alternative 1) and wind (alternative 2) have lower weights.

In the second stage, the synergy of coalition is assessed for hybrid RWB system alternatives. For this purpose, coalition rules are constructed by using the impact-relation directions of the alternatives. Following four coalition rules are defined while considering the details in Figure 2.

Table 3. Weights

	IFSs	PFSs	q-ROFSs
BSS	3	3	4
WND	4	4	3
HDR	2	2	2
SOR	1	1	1

Rule 1: Alternative 1 is ordered before Alternative 4;

Rule 2: Alternative 2 is ordered before Alternative 4;

Rule 3: Alternative 3 is ordered before Alternative 2;

Rule 4: Alternative 4 is ordered before Alternative 3.

Table A7 explains the order the hybrid RWB system alternatives with the coalition rules. Table A8 includes the normalized values. Shapley values in Table A8 state that solar energy is the most beneficial alternative for synergy to increase efficiency in investments. Hydro energy is also appropriate for this situation. Nevertheless, biomass does not have a significant influence on providing synergy in energy investments. Table 4 includes comparative ranking results.

Table 4. Ranking results

	q-ROF Multi SWARA	PF Multi SWARA	IF Multi SWARA
BSS	4	4	4
WND	3	3	3
HDR	2	2	2
SOR	1	1	1

Table 4 indicates that results are same for all different calculations. The findings of the suggested model are coherent. Based on the analysis results, it is seen that solar energy should be prioritized for hybrid energy investments. Solar energy provides the most efficiency in such projects. Hydropower and wind are other critical renewable energy types to generate hybrid energy projects more effectively. According to these issues, a combination can be generated by integrating solar energy with wind or hydropower energy. With the help of this issues, energy efficiency can be provided and interruptions in the energy productions because of climate conditions can be minimized. Finally, a sensitivity analysis is also applied by considering four different cases with the aim of measuring the coherency of the findings. Table 5 gives information about the sensitivity analysis results.

Table 5. Sensitivity analysis results

Alternatives	Case 1	Case 2	Case 3	Case 4
BSS	4	4	4	4
WND	3	3	3	3
HDR	2	2	2	2
SOR	1	1	1	1

Table 5 states that sensitivity analysis results are the same for each different case. Therefore, it is understood that the proposed model provides coherent and reliable findings.

5. Discussion

Solar energy should be prioritized for hybrid energy investments. Solar energy provides the most efficiency in such projects. It is possible to produce high amount of electricity from solar energy projects. In addition, Kumar et al. (2023) determined that technological innovations have also significantly reduced the costs of solar energy projects. Owing to these developments, the efficiency of solar energy investments increases significantly. Thus, Li et al. (2024) and Chen and Zhang (2024) stated that solar energy investments have become quite suitable for increasing the synergy in hybrid energy projects. In addition, biomass energy type cannot contribute significantly to these projects. In this context, it is very important to conduct the necessary research to make biomass energy more efficient. Pascasio et al. (2021), Qi et al. (2021), Castro et al. (2022) and Song et al. (2022) also claimed that for the effectiveness of the hybrid energy systems, solar energy should be preferred.

Furthermore, to increase the effectiveness of hybrid energy projects, solar energy should be integrated with other renewable energy projects. In this context, solar and wind energy projects are investments that complement each other. Soyturk et al. (2024), Doile et al. (2022) and Garcia et al. (2022) identified that the important point here is that while solar panels produce more electricity during the day, wind turbines operate more efficiently at night. Therefore, by integrating these two types of renewable energy, interruptions in energy production can be minimized. On the other hand, Prakasam et al. (2023) and Kirim et al. (2022) mentioned that solar energy can also be integrated with hydroelectric power plants. In this way, electricity can be obtained with solar energy in cases where water flow is not sufficient. Niaz et al. (2024) underlined that this significantly contributes to increasing efficiency in electricity production. Moreover, Al-Khayyat et al. (2023) concluded that this also allows energy storage systems to operate more effectively. It is also possible to increase the efficiency of storage processes by combining different types of alternatives (Mathesh & Saravanakumar, 2023).

6. Conclusions

This paper aims to figure out the synergy of coalition for hybrid RWB system alternatives. For this purpose, the alternative sources of hybrid RWB system are evaluated to illustrate the impact-relation directions among them with q-ROF multi SWARA. Then, the performances of renewable alternatives are measured in terms of the synergy of coalition by using the game theory and Shapley value respectively. The results are given to understand which RWB alternative is the most prominent and how the alternatives can be used efficiently in the limitations of the synergy of coalition. The results are same for all different calculations which shows that the findings of the proposed model are coherent. Biomass and wind have an impact on solar. Moreover, hydro is influenced by solar. Furthermore, wind is affected by hydro. Additionally, solar has the highest weight for all calculations. Additionally, hydro is another crucial RWB type. Also, biomass and wind have lower weights. Solar energy is the most suitable RWB alternative for synergy to increase efficiency in investments. Hydro energy is also appropriate for this situation whereas biomass does not have a significant influence on providing synergy in energy investments.

The novelties of this study can be listed as to extend the SWARA method for employing the impact directions of the alternatives dynamically and integrate the methodologies of game theory and golden ratio to MCDM models. It is assumed that all four different RWB types will be invested simultaneously that is the most important limitation. More specific examples can be focused on in new analyzes. In this framework, hybrid energy projects created with two different types of RWB can also be considered. On the other hand, different analysis methods can also be used in new examinations. DEMATEL method, like SWARA, can detect both criterion weights and causality relationship. The proposed decision-making model has also some limitations. In this model, the evaluations of all experts are considered as equal. However, experts may have different qualifications because of some demographic issues, such as educational level. Due to this condition, in the following studies, new decision-making models should be generated in which the weights of the experts are calculated.

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Author contributions

Conceptualization, Hasan Dinçer (H.D.), Serhat Yüksel (S.Y.), Ümit Hacioğlu (Ü.H.) and Ştefan Cristian Gherghina (Ș.C.G); methodology, H.D., S.Y., Ü.H. and Ș.C.G; software, H.D., S.Y., Ü.H. and Ș.C.G; validation, H.D., S.Y., Ü.H. and Ș.C.G; formal analysis, H.D., S.Y., Ü.H. and Ș.C.G; investigation, H.D., S.Y., Ü.H. and Ș.C.G; resources, H.D., S.Y., Ü.H. and Ș.C.G; data curation, H.D., S.Y., Ü.H. and Ș.C.G; writing – original draft preparation, H.D., S.Y., Ü.H. and Ș.C.G; writing – review and editing, H.D., S.Y., Ü.H. and Ș.C.G; visualization, H.D., S.Y., Ü.H. and Ș.C.G; supervision, H.D., S.Y., Ü.H. and Ș.C.G; project administration, H.D., S.Y., Ü.H. and Ș.C.G; funding acquisition, H.D., S.Y., Ü.H. and Ș.C.G. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare that they have no competing interests.

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APPENDIX

Table A1. Evaluations

Decision Maker 1				
	BSS	WND	HDR	SOR
BSS		H	H	M
WND	M		S	VH
HDR	H	VH		M
SOR	H	M	VH	
Decision Maker 2				
	BSS	WND	HDR	SOR
BSS		M	H	VH
WND	M		M	VH
HDR	H	VH		H
SOR	H	VH	VH	
Decision Maker 3				
	BSS	WND	HDR	SOR
BSS		S	H	VH
WND	VH		M	H
HDR	H	VH		M
SOR	H	H	VH	

Table A2. Average values

	BSS		WND		HDR		SOR	
	μ	v	μ	v	μ	v	μ	v
BSS			0.50	0.31	0.55	0.34	0.57	0.35
WND	0.53	0.33			0.48	0.30	0.58	0.36
HDR	0.55	0.34	0.60	0.37			0.52	0.32
SOR	0.55	0.34	0.55	0.34	0.60	0.37		

Table A3. Score functions

	BSS	WND	HDR	SOR
BSS	0.000	0.095	0.127	0.139
WND	0.116	0.000	0.086	0.152
HDR	0.127	0.165	0.000	0.105
SOR	0.127	0.127	0.165	0.000

Table A4. Critical values

BSS	Sj	kj	qj	Wj	WND	Sj	kj	qj	wj
SOR	0.139	1.000	1.000	0.371	SOR	0.152	1.000	1.000	0.367
HDR	0.127	1.127	0.887	0.329	BSS	0.116	1.116	0.896	0.329
WND	0.095	1.095	0.810	0.300	HDR	0.086	1.086	0.825	0.303
HDR	Sj	kj	qj	Wj	SOR	Sj	kj	qj	wj
WND	0.165	1.000	1.000	0.372	HDR	0.165	1.000	1.000	0.360
BSS	0.127	1.127	0.887	0.330	WND	0.127	1.127	0.887	0.320
SOR	0.105	1.105	0.803	0.298	BSS	0.127	1.127	0.887	0.320

Table A5. Relation matrix

	BSS	WND	HDR	SOR
BSS		0.300	0.329	0.371
WND	0.329		0.303	0.367
HDR	0.330	0.372		0.298
SOR	0.320	0.320	0.360	

Table A6. Stable matrix

	BSS	WND	HDR	SOR
BSS	0.246	0.246	0.246	0.246
WND	0.248	0.248	0.249	0.248
HDR	0.249	0.249	0.249	0.249
SOR	0.257	0.257	0.257	0.257

Table A7. Order of alternatives

Order of Alternatives	BSS	WND	HDR	SOR
1,2,3,4	0.246	0.248	0.000	0.000
1,3,2,4	0.246	0.248	0.249	0.000
1,4,2,3	0.246	0.000	0.000	0.257
1,2,4,3	0.246	0.248	0.000	0.257
1,3,4,2	0.246	0.000	0.249	0.000
1,4,3,2	0.246	0.000	0.249	0.257
2,1,3,4	0.246	0.248	0.000	0.000
2,3,1,4	0.246	0.248	0.000	0.000
2,4,1,3	0.000	0.248	0.000	0.257
2, 1, 4, 3	0.246	0.248	0.000	0.257
2, 3, 4, 1	0.000	0.248	0.000	0.000
2, 4, 3, 1	0.000	0.248	0.000	0.257
3, 2, 1, 4	0.246	0.248	0.249	0.000
3, 1, 2, 4	0.246	0.248	0.249	0.000

End of Table A7

Order of Alternatives	BSS	WND	HDR	SOR
3, 4, 2, 1	0.000	0.000	0.249	0.000
3, 2, 4, 1	0.000	0.248	0.249	0.000
3, 1, 4, 2	0.246	0.000	0.249	0.000
3, 4, 1, 2	0.000	0.000	0.249	0.000
4, 2, 3, 1	0.000	0.000	0.000	0.257
4, 3, 2, 1	0.000	0.000	0.249	0.257
4, 1, 2, 3	0.000	0.000	0.000	0.257
4, 2, 1, 3	0.000	0.000	0.000	0.257
4, 3, 1, 2	0.000	0.000	0.249	0.257
4, 1, 3, 2	0.000	0.000	0.249	0.257

Table A8. Normalized values

Order of alternatives	BSS	WND	HDR	SOR
1, 2, 3, 4	0.498	0.502	0.000	0.000
1, 3, 2, 4	0.331	0.334	0.335	0.000
1, 4, 2, 3	0.489	0.000	0.000	0.511
1, 2, 4, 3	0.327	0.331	0.000	0.342
1, 3, 4, 2	0.497	0.000	0.503	0.000
1, 4, 3, 2	0.327	0.000	0.331	0.342
2, 1, 3, 4	0.498	0.502	0.000	0.000
2, 3, 1, 4	0.498	0.502	0.000	0.000
2, 4, 1, 3	0.000	0.492	0.000	0.508
2, 1, 4, 3	0.327	0.331	0.000	0.342
2, 3, 4, 1	0.000	1.000	0.000	0.000
2, 4, 3, 1	0.000	0.492	0.000	0.508
3, 2, 1, 4	0.331	0.334	0.335	0.000
3, 1, 2, 4	0.331	0.334	0.335	0.000
3, 4, 2, 1	0.000	0.000	1.000	0.000
3, 2, 4, 1	0.000	0.500	0.500	0.000
3, 1, 4, 2	0.497	0.000	0.503	0.000
3, 4, 1, 2	0.000	0.000	1.000	0.000
4, 2, 3, 1	0.000	0.000	0.000	1.000
4, 3, 2, 1	0.000	0.000	0.492	.508
4, 1, 2, 3	0.000	0.000	0.000	1.000
4, 2, 1, 3	0.000	0.000	0.000	1.000
4, 3, 1, 2	0.000	0.000	0.492	0.508
4, 1, 3, 2	0.000	0.000	0.492	0.508
Shapley Values	0.206	0.236	0.263	0.295