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Synergistic integration of digital twins and sustainable industrial internet of things for new generation energy investments

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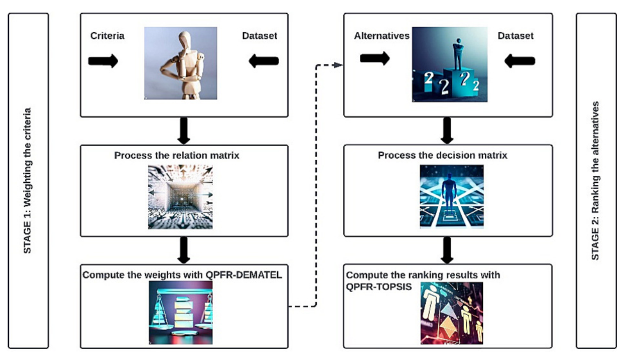
HIGHLIGHTS

- Using DEMATEL for causal relationship analysis of determinants in digital twin performance.
- Synergy of Quantum picture fuzzy rough sets & Quantum theory to enhance digital twin policies for renewables.
- Criteria list based on TBL technique for evaluating social, environmental, & economic impacts.
- Importance of analyzing climatic conditions for risk identification & sustainable results.
- Strong infrastructure & up-to-date tech crucial for accurate data analysis in digital twins.

GRAPHICAL ABSTRACT



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ABSTRACT

Introduction: This study aims to identify optimal digital twin policies for enhancing renewable energy projects. Through a comprehensive analysis, the research evaluates the potential of digital twins in the renewable energy sector while considering triple bottom line perspectives.
Objectives: The study's main goal is to prioritize digital twin policies that can effectively boost renewable energy projects. The research aims to demonstrate the practical application and reliability of a proposed evaluation model.
Methods: Nine criteria, derived from literature review and triple bottom line viewpoints, are selected. Using the decision-making trial and evaluation laboratory (DEMATEL) methodology and Quantum picture fuzzy rough sets, criteria weights are determined. Quantum picture fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) evaluates sustainable industrial internet of things strategies in new-gen energy investments. VIsekriterijumska optimizcija i KOmpromisno Resenje (VIKOR) methodology enables a comparative assessment, and sensitivity analysis is conducted across nine cases.
Results: Consistent outcomes across various methods validate the model's reliability. Ecosystem preservation carries the highest weight (0.1147), followed by resource policy optimization with digital twins

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(0.1139). Distributed energy resilience ranks first (RCi 0.576), closely followed by energy efficiency optimization (RCi 0.542).

Conclusion: This study underscores ecosystem preservation and efficient resource policies as pivotal for successful digital twin deployment in renewable energy projects. The findings highlight digital twins' potential contribution to environmental protection and ecosystem sustainability, emphasizing resource efficiency through their effective use.

Introduction

Digital twins, in the context of this study, refer to virtual representations of real-world systems that simulate the behavior and performance of these systems, enabling early problem detection and system improvement. In this process, the properties of this real system are simulated. In this way, the performance of these systems can be followed in detail. Thus, problems occurring in the system can be detected at early levels. This condition allows the necessary steps to be taken to improve the system in a timely manner. In this way, it is possible for the system to work more successfully. This situation can help both to ensure the sustainability of the projects and to ensure customer satisfaction. On the other hand, digital twins greatly contribute to the optimization of business processes [1]. In addition, digital twins can also help develop innovative new products. Thanks to the tests carried out at this stage, the process can work more effectively. In this context, new features that are necessary to improve the process can be determined. In this way, it becomes easier for the products to be developed to be both innovative and successful.

Digital twins are of great importance in the energy sector and provide many benefits in the management of energy investments. Owing to this system, it is possible to increase the efficiency of energy production and distribution processes. This system can effectively monitor the performance indicators in the production process of the enterprises. In other words, digital twins significantly help to detect disruptions in energy production beforehand. Increasing the efficiency in energy demand management is also possible thanks to digital twins. This allows energy investors to plan better [2]. On the other hand, digital twins make a significant contribution to increasing the use of clean energy. Owing to this system, it is possible to increase the cost-effectiveness of clean energy projects. This condition allows renewable energy projects to compete with fossil fuels in terms of financial profitability [3]. In addition, digital twins are of great benefit in the maintenance and failure management of power generation equipment. In this way, it is possible to prevent possible malfunctions and quickly correct them.

Some issues need to be considered to increase the performance of digital twins used in renewable energy investments. In this process, it is necessary to improve the quality of the obtained data as a priority. In the digital twin system, real-time data can be collected and analyzed. In this context, the data provided must be accurate and reliable. Otherwise, digital twins will produce erroneous strategies. To increase the positive effects of digital twins on renewable energy investments, the obtained data should be analyzed quickly and accurately. To achieve this goal, necessary technological improvements should be made. Within this framework, artificial intelligence techniques can be used to improve the performance of digital twins [4]. In this way, it is possible to make more effective estimations about energy production and consumption. This contributes significantly to increasing the efficiency of investments. On the other hand, making continuous improvements is a necessary aspect to improve the performance of digital twins. In this context, it is important to provide the necessary feedback for the process.

Both social, environmental, and economic factors are very important to increase the performance of digital twins in renewable energy projects. Within the framework of economic factors, issues such as the efficiency of the process, its financial viability and its contribution to economic growth are important. Additionally, paying attention to climatic conditions, effective use of natural resources and protecting the ecosystem are very effective under environmental issues. However, issues such as social equality, health and safety should also be analyzed in the context of social factors [5]. On the other hand, improving all these factors causes the financial costs of enterprises to increase very much. In other words, considering that enterprises have budget constraints, many improvements to this process lead to an uncontrolled increase in costs. Therefore, it is necessary to find the most important of these factors. This situation allows businesses to present the specific strategies necessary to increase their digital twin performance more effectively.

This study aims to identify the most appropriate digital twin policies for renewable energy projects. In the analysis process, first, the weights of the determinants are computed. For this purpose, these factors are selected based on the perspectives of the triple bottom line approach. In this context, DEMATEL methodology based on Quantum picture fuzzy rough sets is taken into consideration. Secondly, strategy alternatives for sustainable industrial internet of things in new generation energy investments are examined by using Quantum picture fuzzy TOPSIS.

The main contributions of the study are indicated as follows.

(i) Considering picture fuzzy rough sets with Quantum theory provides a significant methodological novelty. A wide range of data can be examined by picture fuzzy sets in comparison with the traditional fuzzy sets. This situation has a powerful contribution to handling uncertainties in the process more effectively [6]. Similarly, Quantum theory is considered to make sensitive evaluation. Hence, using this theory in this process helps to consider different probabilities. Owing to this condition, more comprehensive evaluations can be carried out [7].

(ii) Creating a criteria list based on the perspectives of the triple bottom line technique provides some benefits. Both social, environmental, and economic factors may have an effect on the performance of digital twins in renewable energy projects. The triple bottom line technique is used to evaluate the sustainability performance of businesses. In this context, the economic, environmental, and social impacts of businesses are analyzed. In this way, it allows businesses to measure and report their performance and impacts more comprehensively. Additionally, it helps businesses to make better risk management.

(iii) On the other hand, using DEMATEL technique in the weighting of these criteria brings some advantages. This approach uses causal directions of the factors while computing the weights of the criteria. The determinants of the digital twin performance can affect each other [8]. Therefore, while making analysis for this subject, the causality relationship should be taken into consideration. Due to this issue, DEMATEL methodology is more appropriate for this situation while comparing with other similar techniques [9].

The second part focuses on literature evaluation. Methodology is explained in the next section. The fourth part gives information on the results of the proposed model. The findings are discussed in the fifth part. The final section highlights the conclusions.

Literature review

Previous research has emphasized the crucial role of financial efficiency in investment decision-making [10]. One of the most important issues when making an investment decision is financial efficiency. Digital twins can simulate the improvements of these projects. [11] denoted that in this way, the possible risks and expected returns of an investment project can be understood. This situation makes a significant contribution to the fact that enterprises can be more effective in cost management. On the other hand, according to [12], thanks to digital twins, businesses can perform resource management more successfully. In this context, business processes can become more efficient. Thus, it is possible to increase the profitability of the projects in the long run. Moreover, [13] identified that by using digital twins, the performance of projects can be monitored comprehensively. In this way, disruptions in processes can be detected early. This situation allows for minimizing job losses [14]. In this way, it is possible for enterprises to take measures to increase their financial performance.

For digital twins to be implemented more successfully, it is necessary to pay attention to climatic conditions. [15] mentioned that climate change has a direct impact on the performance of investments in many sectors. Thanks to the analysis of these conditions, it can be much easier to identify the possible risks of the projects. In this case, it helps to solve the problems that may occur more successfully [16]. On the other hand, climatic conditions also play a critical role in the management of energy demands. [17] defined that with the purpose of increasing the performance of digital twins, energy needs must be met effectively. In this process, climatic conditions must be accurately predicted. To analyze the environmental effects correctly, it is necessary to pay attention to the climatic conditions. According to [18], this is especially important for the sustainability of projects. Therefore, a proper understanding of environmental impacts is required for digital twins to produce successful results. Furthermore, [19] determined that for a project to be successful, the infrastructure design must be suitable for different conditions. Therefore, the analysis of climatic conditions is important in terms of determining the durability of the infrastructure of these projects.

A strong technological infrastructure is also necessary for the more successful implementation of digital twins. [20] explained that in the working process of digital twins, very large amounts of data are analyzed. It is very important in this process that this data can be obtained accurately. To achieve this goal, businesses must have a strong technological infrastructure [21]. Another important issue for the successful operation of digital twins is the correct analysis of this data. To achieve this, businesses need to use up-to-date technology. Similarly, [22] explained that it is important to evaluate different scenarios so that digital twins can develop accurate results. This allows investment projects to be planned more accurately [23]. In this context, businesses should be able to use up-to-date technology to carry out an effective analysis. Moreover, [24] showed that confidential information of customers can also be analyzed in the digital twin system. In this context, necessary security measures should be taken to prevent unauthorized persons from accessing this confidential information. In other words, it is important to make up-to-date technological investments and take necessary precautions regarding data security.

Inclusive participation plays an important role in improving the performance of digital twins used in investments. This issue refers to the active participation of all stakeholders in investment projects. Inclusive participation, which involves active engagement of stakeholders, can lead to diverse data sources being accessed, thereby enhancing the diversity and reliability of data used in digital twins [13]. This is very important in increasing the success of investments. Therefore, according to [25], it is necessary to ensure inclusive participation in digital twins as well. On the other hand, inclusive participation improves data quality and access. In this framework, [26] determined that data diversity can increase as different sources can be accessed by involving stakeholders more effectively in the process. Furthermore, [27] identified that as a result of the participation of stakeholders in the process, the accuracy and reliability of the data used in digital twins can be increased. Thanks to the opinions received from different stakeholders, it becomes easier to detect the disruptions in the process [28]. Thus, it is possible to solve the problems within a reasonable time. Moreover, [29] underlined that the inclusion of different stakeholders in the process also increases the ethical compliance of the process. Owing to the opinions of different people, it is possible to understand possible unethical issues.

The main findings in literature examinations are demonstrated below. Digital twin has a powerful impact in the performance of business investments. In addition to this issue, social, environmental, and economic factors are very important to increase the performance of digital twins. However, improving all these factors causes the financial costs of enterprises to increase very much. Therefore, it is necessary to find the most important of these factors. Nevertheless, it is seen that very few researchers concentrate on this issue. As can be seen from this situation, a new study in which the criteria of the most importance will be determined will be beneficial in many respects. To meet this need, in this study, it is aimed to determine the issues that have the most impact on the performance of digital twins.

Methodology

The methods used in this model are explained in this section. All equations are demonstrated in the appendix part. Considering picture fuzzy rough sets with Quantum theory provides a significant methodological novelty. A wide range of data can be examined by picture fuzzy sets in comparison with the traditional fuzzy sets. Similarly, Quantum theory is considered to make sensitive evaluation. Hence, using this theory in this process helps to consider different probabilities. On the other hand, using DEMATEL technique in the weighting of these criteria brings some advantages. This approach uses causal directions of the factors while computing the weights of the criteria. Furthermore, TOPSIS technique considers the distances to both positive and negative optimal solutions. This situation has a positive influence on the appropriateness of the findings.

Modelling uncertainty with Quantum picture fuzzy rough sets with golden cuts

Quantum theory considers different probabilities in the evaluation process. Because it is helpful to make appropriate predictions about the future values, more sensitive calculations can be performed with the help of this theory. In this study, it is integrated into picture fuzzy rough sets [9]. The explanations are given in Eqs. (1)-(3). In this context, Q indicates quantum theory, u is the event, θ represents the phase angle and φ^2 indicates the amplitude [7]. The conventional fuzzy set (A) is identified in Eq. (4) where the membership function is shown as x and μ_A refers to the membership degree. Intuitionistic fuzzy sets include both membership and non-membership functions as in Eq. (5). Picture fuzzy sets include additional function parameters as in Eq. (6) [30]. The main operations are identified in Eqs. (7)-(11). Rough numbers are an extension of this set that is used for minimizing the subjective and uncertain evaluations. Eqs. (12)-(14) indicate these items in which *apr* and *bnd* identify the approximation and boundaries [31]. Lower ($\underline{Lim}(C_i)$), upper ($\overline{Lim}(C_i)$) limits and the rough number ($RN(C_i)$) are stated in Eqs. (15)-(17) where N_L and N_U indicate the number of objects for $\underline{Apr}(C_i)$ and $\underline{Apr}(C_i)$. The proposed model in this study includes the integration of picture fuzzy rough sets and Quantum theory that is detailed in Eq. (18). This equation is firstly generated by the authors with the help of integration the quantum theory with picture fuzzy rough sets. In this scope, $C_{i\mu_A}$ refers to the membership, C_{in_A} demonstrates the neutral degree, C_{iv_A} explains the non-membership, and C_{ih_A} indicates the refusal degrees. Picture fuzzy rough numbers of them are identified in Eqs. (19)-(26). Additionally, $N_{L\mu_A}$, N_{Ln_A}, N_{Lv_A}, N_{Lh_A} show the numbers in $\underline{Apr}(C_{i\mu_A})$, $\underline{Apr}(C_{in_A})$, $\underline{Apr}(C_{iv_A})$, $\underline{Apr}(C_{ih_A})$ respectively while $N_{U\mu_A}$, N_{Un_A}, N_{Uv_A}, N_{Uh_A} are identified for $\underline{Apr}(C_{i\mu_A})$, $\underline{Apr}(C_{in_A})$, $\underline{Apr}(C_{iv_A})$, $\underline{Apr}(C_{ih_A})$. The details are demonstrated in Eqs. (27)-(34). Quantum picture fuzzy sets are explained in Eqs. (35) and (36). Owing to the integration of both quantum theory and picture fuzzy rough sets, more sensitive evaluations can be conducted. This situation helps to overcome uncertainty problems in the fuzzy decision-making analysis more effectively. The degrees are computed with golden ratio (G) in this study. The process is explained in Eqs. (37) and (38) [9]. The phase angles of the degrees are shown in Eqs. (39)-(41). Eqs. (42)-(45) identify the main operations.

DEMATEL with Quantum picture fuzzy rough sets

DEMATEL approach weights the criteria by considering their impact-relation directions [32]. The evaluations are obtained from the experts. Eq. (46) is used to generate relation matrix [33]. The aggregated values are calculated in Eq. (47). The values are defuzzified with Eq. (48). Normalized values are computed by Eqs. (49) and (50). Eq. (51) is used to create total relation matrix. Eqs. (52) and (53) are used to calculate D and E that are the sums of rows and columns. Eq. (54) is considered for computing threshold value that is used to generate causal directions.

TOPSIS with Quantum picture fuzzy rough sets

TOPSIS is considered to rank alternatives [34]. This technique is used with Quantum picture fuzzy rough numbers in the analysis process of the study. Firstly, evaluations are provided from the experts. With Eq. (55), decision matrix is constructed [6]. Eq. (48) is taken into consideration to compute the defuzzified values. The values are normalized in the following step by Eq. (56). The values are weighted by Eq. (57). The positive and negative ideal solutions, A^+ and A^-, are computed with Eqs. (58) and (59). Eqs. (60) and (61) are used to identify the distances to the best and worst alternatives, D_i^+ and D_i^-. With Eq. (62), the relative closeness can be computed.

VIKOR with Quantum picture fuzzy rough sets

VIKOR helps to rank different alternatives. The first 3 steps are similar to TOPSIS. In the following step, the best $\tilde{f}_J^*$ and worst $\tilde{f}_j^-$ values are computed as in Eq. (63) [35]. Eqs. (64) and (65) are considered to identify the mean group utility and maximal regret. By using Eq. (66), the final ranking can be computed. There are mainly two conditions that should be satisfied. According to the first condition, Eq. (67) should be fulfilled. Additionally, regarding the second condition, the alternative must be the best ranked by either S or R, or both.

Analysis results

The steps of the proposed model are denoted in Fig. 1.

Weighting the digital twin policies for renewable projects (Stage 1)

In the first step, the dimensions and criteria are identified. In this scope, the perspectives of the triple bottom line approach are taken into consideration that are economic, environmental, and social. Table 1 underlines these policies.

Table 1 gives information that there are mainly 9 different digital twin policies for renewable energy projects based on 3 dimensions. Different questions are created by comparing these items to each other. Three experts have given their evaluations by answering these questions. In this process, the scales in Table A1 are considered. Evaluations are given in Table A2. Relation matrix is created by Eq. (46). Quantum picture fuzzy rough sets for the relation matrix are given in Table A3. The values are defuzzified with Eq. (48). After that, normalized values are calculated with Eqs. (49) and (50). Total relation matrix is constructed with Eq. (51). The weights are calculated by using the sum of the rows and columns as in Eqs. (52) and (53). Table 2 denotes both total relation matrix and the weights of the policies.

Table 2 presents that ecosystem preservation supported by digital twin has the greatest weight (0.1147). This condition explains that it is the most important digital twin policies for renewable projects. Resource policy optimization with digital twin also has a high weight (0.1139). It shows that this situation should also be taken into consideration in this process.

Ranking the strategy alternatives for sustainable industrial internet of things in new generation energy investments (Stage 2)

In the second phase of the proposed model, strategy alternatives are evaluated in new generation energy investments. In this context, firstly, five different alternatives are identified according to the literature review results. They are explained in Table 3.

After that, the linguistic evaluations of decision makers for the alternatives are collected. Next, quantum picture fuzzy numbers are created. Later, Eq. (55) is considered to create decision matrix as in Table A4. In the following step, the defuzzified decision values are computed by using Eq. (48). After that, the values are normalized by Eq. (56). Next, the weighted decision values are calculated with Eq. (57). Finally, Eqs. (58)-(62) are taken into consideration to compute the ranking results. The results shows that distributed energy resilience is the most significant strategy alternative in new generation energy investments because of the highest RCi value (0.576). Similarly, energy efficiency optimization is also found as the second most significant factor in this framework with the RCi value of 0.542. Distributed energy investments play an important role in increasing the performance of the digital twin in clean energy projects. Distributed energy investments include the local generation and use of renewable energy sources. Thanks

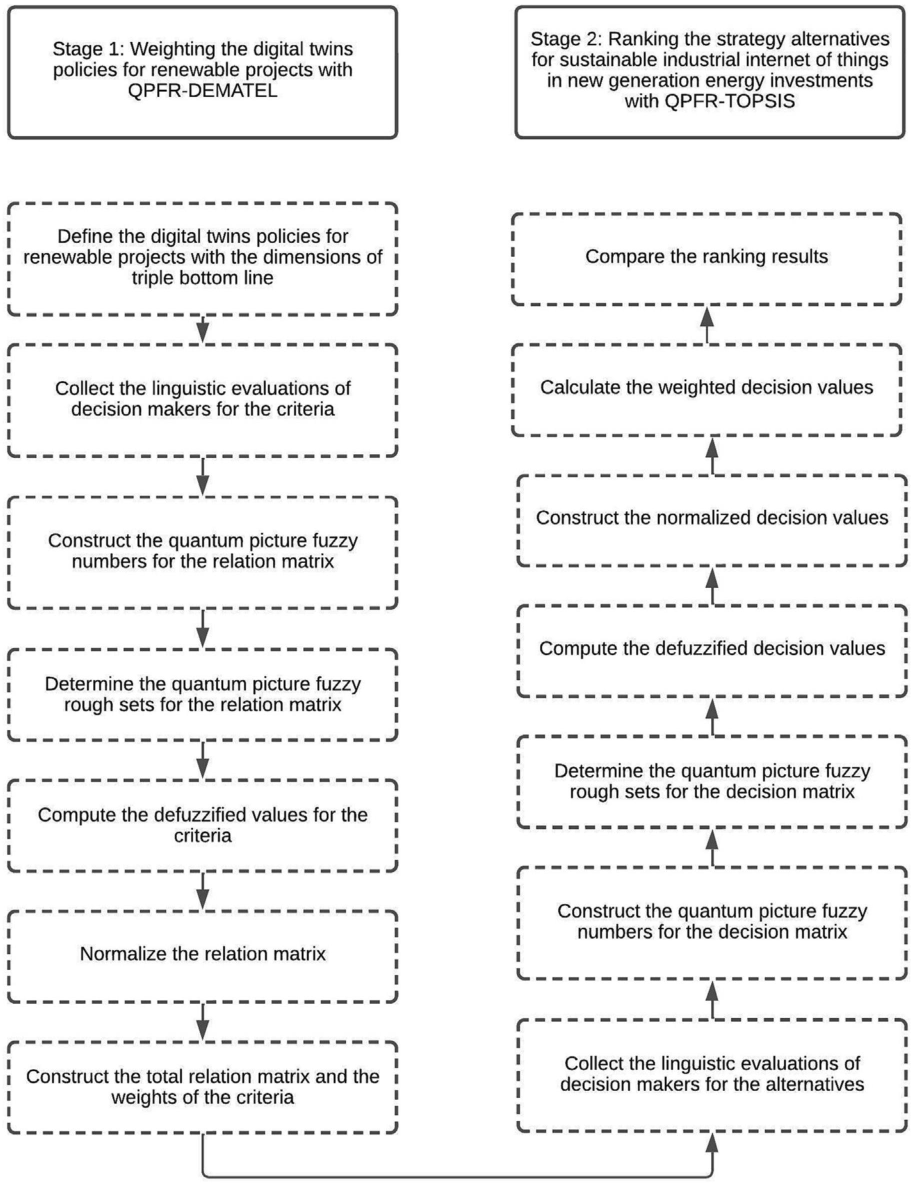

Fig. 1. The algorithm of hybrid model.

Table 1
Digital twin policies for renewable projects with the dimensions of triple bottom line.

Dimensions	Criteria	References
Economic Dimension	Efficiency in virtual-real integration (VRGT)	[36]
	Financial viability of digital twin applications (VTPP)	[37]
	Economic growth enabled by digital twin (MCGW)	[38]
Environmental Dimension	Climate action through digital twin implementation (CLNT)	[23]
	Resource policy optimization with digital twin (RPMZ)	[20]
	Ecosystem preservation supported by digital twin (CSYV)	[39]
Social Dimension	Inclusive participation in digital twin initiatives (SVNS)	[40]
	Social equity considerations in virtual-real integration (CQGR)	[13]
	Health and safety benefits of digital twin technologies (HSTC)	[4]

to digital twins, it is possible to monitor the performance of these systems in a comprehensive way. This, in turn, contributes to increasing the performance of distributed energy generation systems. Thus, it is possible to increase the efficiency of energy production processes. In addition to these issues, the reliability and coherency of the findings are also tested. In this framework, a comparative evaluation has also been performed by using VIKOR methodology. Furthermore, by using 9 different cases, a sensitivity analysis is also performed. Comparative ranking results with sensitivity analysis are given in Table 4.

Table 4 indicates that the results are quite similar. For example, distributed energy resilience is the best alternative for all cases in both models. This situation gives information that the findings of the proposed model are coherent and reliable.

Discussions

Priority should be given to protecting the ecosystem to increase the performance of digital twins used for renewable energy projects. Digital twins contribute significantly to environmental pro-

Table 2
Total relation matrix and the weights of the criteria.

	VRGT	VTPP	MCGW	CLNT	RPMZ	CSYV	SVNS	CQGR	HSTC	Weights
VRGT	1.933	2.028	2.068	1.955	2.058	2.061	2.075	2.048	2.028	0.1108
VTPP	2.024	1.900	2.061	1.954	2.065	2.054	2.064	2.027	2.004	0.1098
MCGW	2.015	2.012	1.940	1.948	2.050	2.048	2.050	2.034	2.003	0.1110
CLNT	2.121	2.088	2.141	1.936	2.161	2.156	2.153	2.118	2.104	0.1109
RPMZ	2.128	2.098	2.146	2.047	2.043	2.152	2.144	2.119	2.104	0.1139
CSYV	2.151	2.122	2.176	2.083	2.191	2.071	2.184	2.162	2.121	0.1147
SVNS	1.999	1.955	2.005	1.908	2.016	2.020	1.914	2.005	1.966	0.1103
CQGR	2.040	2.012	2.076	1.972	2.075	2.086	2.087	1.948	2.036	0.1112
HSTC	1.922	1.900	1.944	1.855	1.973	1.967	1.955	1.932	1.813	0.1073

Table 3
Strategy alternatives for sustainable industrial internet of things in new generation energy investments.

Alternatives	References
Renewable Energy Advancements (REA)	[3;41]
Intelligent IoT Integration (IOT)	[15]
Market-based Sustainability Incentives (MSI)	[29]
Energy Efficiency Optimization (EEO)	[42;43]
Distributed Energy Resilience (DER)	[36]

tection and sustainability of the ecosystem. Primarily, it is possible to ensure resource efficiency through the effective use of digital twins. Owing to the instant data analysis in digital twins, the places where resources are used unnecessarily can be determined. [44] highlighted that thanks to the measures to be taken for this situation, energy savings can be achieved. On the other hand, [45] showed that thanks to the good performance of digital twins, it can be easier to increase energy efficiency. [36] also discussed that in this way, the cost efficiency of the projects will be achieved, and this situation will positively affect the profitability. As a result, it is possible to ensure the sustainability of the projects.

Moreover, the ability of digital twins to analyze current data effectively also contributes to the success of waste management. Waste management is an important issue to increase the performance of renewable energy projects [46]. With the successful implementation of digital twins, measures can be taken to reduce waste generation. In addition, the wastes generated must be disposed of correctly. In this context, especially some types of waste may need to be disposed of without waiting too long in the warehouse [40,42]. Otherwise, these wastes cause significant harm to both the environment and people. [38] and [47] showed that thanks to digital twins, it is possible to carry out a comprehensive analysis according to different types of waste. This situation also contributes to a significant increase in the success of waste management. [37] and [48] also highlighted the significance of this situation in their studies.

It has been concluded that distributed energy investments play an important role in increasing the performance of the digital twin in clean energy projects. Thanks to these investments, it is possible to produce and use renewable energy resources locally. Digital twins primarily enable these projects to be examined more comprehensively. This helps to increase efficiency in energy production. Distributed energy investments also support businesses to increase their energy storage technologies. It is possible to make an accurate estimation of energy storage amounts with digital twins. [49] and [50] demonstrated that thanks to the accurate results obtained here, it is possible to manage the energy demand more successfully. Thus, it becomes easier to increase the effectiveness and efficiency of projects. On the other hand, [51] defined that distributed energy investments help to reduce carbon emissions by promoting the use of clean energy. According to [39], digital twins can also examine the energy production process more effectively and identify processes with high carbon emissions. This situation helps to take more effective measures to solve this problem.

The proposed model is the study has also some superiorities in comparison with previously generated models. In this process, firstly, integrating picture fuzzy rough sets with Quantum theory provides some advantages. With the help of this integration, uncertainty in the analysis process can be handled more effectively than other models [52–54]. However, the proposed model has also some limitations. For the purpose of weighting the criteria, DEMATEL methodology is taken into consideration [55]. However, this methodology is criticized because of some issues. Because of this issue, new models are created in the literature, such as TOP-DEMATEL and M−SWARA to overcome this situation [56]. Similarly, some scholars also criticized TOPSIS and VIKOR due to the analysis process. To solve these problems, new ranking techniques are also generated in the literature, such as RATGOS [57].

Table 4
Comparative ranking results with sensitivity analysis.

Extended TOPSIS									
Alternatives	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
REA	3	3	3	3	3	3	3	3	3
IOT	5	5	5	5	4	4	4	5	5
MSI	4	4	4	4	5	5	5	4	4
EEO	2	2	2	2	2	2	2	2	2
DER	1	1	1	1	1	1	1	1	1
Extended VIKOR									
Alternatives	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
REA	3	3	3	3	3	3	3	4	3
IOT	5	5	5	5	4	4	5	5	5
MSI	4	4	4	4	5	5	4	3	4
EEO	2	2	2	2	2	2	2	2	2
DER	1	1	1	1	1	1	1	1	1

Conclusion

This study tries to determine the most suitable digital twin policies for renewable energy projects. In the analysis process, first, the weights of the indicators are calculated. Within this context, these items are selected based on the perspectives of the triple bottom line approach. DEMATEL methodology based on Quantum picture fuzzy rough sets is taken into consideration to calculate the weights of these factors. In the second phase, strategy alternatives for sustainable industrial internet of things in new generation energy investments are examined by using Quantum picture fuzzy TOPSIS. It is determined that ecosystem preservation supported by digital twin has the highest weight (0.1147). This situation identifies that it is the most significant digital twin policies for renewable projects. Resource policy optimization with digital twin also has a high weight (0.1139). It shows that this situation should also be taken into consideration in this process.

According to the ranking results, it is also concluded that distributed energy resilience is the most significant strategy alternative in new generation energy investments because of the highest RCi value (0.576). Similarly, energy efficiency optimization is also found as the second most significant factor in this framework with the RCi value of 0.542. However, market-based sustainability incentives and intelligent IoT integration are on the last rankings. This condition explains that these factors have a lower significance in comparison with the others. In this framework, a comparative evaluation has also been performed by using VIKOR methodology. Furthermore, by using 9 different cases, a sensitivity analysis is also performed. It is seen that the results are quite similar. This situation gives information that the findings of the proposed model are coherent and reliable.

This study has important contributions to the literature in some ways. Firstly, considering picture fuzzy rough sets with Quantum theory provides a significant methodological novelty. This situation has a powerful contribution to handling uncertainties in the process more effectively. Moreover, creating a criteria list based on the perspectives of the triple bottom line technique provides some benefits. Both social, environmental, and economic determinants can have an influence on the performance of digital twins in renewable energy projects. Therefore, creating a criteria list based on the perspectives of the triple bottom line technique provides some benefits. However, there are some important limitations of this study. In the analysis process, renewable energy projects are considered generally. However, the findings can be different for various types of the renewable energy projects. Thus, as a future research direction, a specific renewable energy type can be evaluated with respect to the digital twin performance. Similarly, the results can be compared for different renewable energy types so that specific strategies can be developed. Furthermore, in the following studies, specific country groups can be taken into consideration. For instance, comparing developing and developed economies for this subject has a significant contribution to the literature.

CRediT authorship contribution statement

Gang Kou: Conceptualization, Writing – review & editing. **Hasan Dinçer:** Data curation, Writing – original draft, Methodology, Software. **Serhat Yüksel:** Writing – original draft, Visualization, Investigation. **Muhammet Deveci:** Supervision, Software, Validation, Visualization.

Declaration of Competing Interest

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

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Ethical Compliance: Given the nature of our research, we have ensured ethical compliance within the parameters of our study. We have followed best practices within our field and adhered to any applicable ethical guidelines.

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jare.2023.11.023.

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