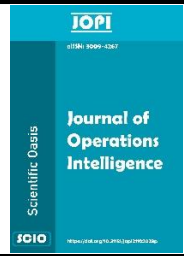




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Offshore Wind Power Site Selection in Türkiye Using q-Rung Orthopair Fuzzy Sets and the COPRAS Method

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ABSTRACT

Wind energy has significant potential for electricity and energy generation. At the same time, Türkiye is among the important markets in wind energy production worldwide. With the increasing energy demand and sustainability goals, energy production is gradually shifting towards offshore wind farms (OWFs). In this study, three alternative locations in the Aegean Sea region of Türkiye were evaluated to determine the most suitable site for OWF installation based on two main and twelve sub-criteria. The methodology applied in the study generally consists of four stages. In the first stage, a normalized weighted decision matrix was created using the steps of the q-rung Orthopair fuzzy set. In the second stage, the COPRAS method, one of the multi-criteria decision-making (MCDM) methods, was applied to rank the alternatives, and the best alternative was determined to be Bozcaada offshore. In the third stage, a comparison analysis was performed using q-ROF TOPSIS and q-ROF WASPAS methods. As a result of the comparison analysis, it was determined that all three methods gave the same results. In the last stage, the sensitivity of all three MCDM methods was checked by changing the q levels. The sensitivity analysis revealed that the q-ROF COPRAS method was insensitive to changes in q levels, while the q-ROF TOPSIS and q-ROF WASPAS methods were sensitive, as the alternative rankings changed as a result of these changes.

1. Introduction

There is an increasing global demand for energy. The preponderance of this energy requirement is met through the utilization of fossil fuels. The depletion of fossil fuels has compelled humanity to explore alternative energy sources [1]. The transition to new energy sources has become imperative in the context of climate change, a phenomenon that has had a global impact. Consequently, there has been an increased focus on the utilization of renewable energy sources for the purpose of generating clean energy. Renewable energy sources are of great significance for nations seeking to

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enhance autonomy from external sources of energy. A plethora of renewable energy sources is available, including solar, wind, geothermal and hydroelectric energy. The increasing tendency towards renewable energy has led to wind energy becoming a prominent source of sustainable energy, with a high potential for energy production.

Wind energy, which is among the most rapidly expanding reliable energy sources, contributes to the mitigation of climate change by virtue of the fact that it does not give rise to the release of greenhouse gases. The conversion of wind energy into electrical energy is the fundamental process at the core of wind energy production. Facilities located on land and at sea are utilized for the purpose of generating wind-generated electricity. Presently, the majority of capacity is land-based. Offshore wind facilities have been identified as having considerable potential for energy production [2].

Due to its high capacity and reduced land constraints, the installation of wind facilities has shifted towards offshore areas over time. Offshore wind turbines have been shown to generate a greater volume of electricity than their onshore counterparts, a phenomenon attributable to the higher wind speeds that they are able to harness [3]. The increasing demand for offshore wind farms can be attributed to two key factors: low environmental impact and limited land space [4]. It is evident that land-based wind power plants have the potential to pose a significant environmental hazard, thereby endangering the avian population [5]. In contradistinction to land-based facilities, offshore wind power plants are characterized by a reduced spatial constraint and a diminished environmental impact [6]. Despite the common advantages inherent in wind power plants, they also possess distinct advantages and disadvantages [7]. It has been demonstrated that the financial outlay required for the construction of offshore wind power plants exceeds that of their land-based counterparts. The inherent challenges posed by the vast marine environment, coupled with the elevated costs associated with operation and maintenance due to logistical constraints, have been thoroughly documented [8-11].

The emergence of offshore wind power plants has been a prominent feature since the early 1990s [1]. The inaugural offshore wind power plant was constructed in Denmark in 1991. In 2020, the average capacity of installed wind turbines was reported to be 8.2 MW [12]. By the year 2050, it is estimated that the potential for offshore wind power will reach 8.6 TW [13].

In 2024, Europe witnessed the installation of 16.4 GW of new wind power capacity. In the preceding year, 84% of newly constructed wind capacity in Europe was located onshore. By 2030, it is projected that 75% of new wind installations will continue to take place onshore. In 2024, wind power accounted for 19% of all electricity consumed across the EU. European governments have allocated a total of 36.8 GW of new wind power capacity in 2024, 17 GW onshore and 19.9 GW offshore in 12 countries. In 2024, Europe witnessed the installation of 16.4 GW of new wind farms. Of these, 13.8 GW are located onshore and 2.6 GW are located offshore. In order for the EU to achieve its 42.5% renewable energy target by 2030, wind power installations must average 36 GW per year between 2025 and 2030. In this particular instance, the objective is to attain 425 GW [14].

It is evident that offshore wind farms generally exhibit a greater magnitude of size in comparison to onshore wind farms. The installation times are significantly prolonged. In 2024, wind farms within the European Union generated 475 TWh of electricity. The study found that wind power met 19% of the electricity demand, with 16.6% of this figure attributable to onshore wind and 2.5% to offshore wind [14]. Figure 1 illustrates the distribution of onshore and offshore wind farms in the EU during the period 2015-2024.

Türkiye is an energy-dependent country, with approximately 75% of its energy being imported. The majority of the electricity generated in the country is derived from fossil fuels. It is evident that the proportion of annual energy derived from renewable sources is minimal, with only 15% of energy

being provided by such sources [1]. Electric energy consumption in Türkiye in 2024 was 347.9 TWh, and generation was 348.9 TWh. In this particular instance, it is evident that the demand for energy has undergone a substantial increase. Energy consumption in Türkiye is projected to reach 455.3 TW in 2030 [15]. In 2034, an average increase of 2.2% is anticipated [16]. In 2024, the following sources were used to generate electricity: 35.2% from coal, 18.9% from natural gas, 21.5% from hydraulic energy, 10.5% from wind, 7.5% from solar, 3.2% from geothermal energy and 3.2% from other sources. By the close of April 2025, the number of electricity generation plants in Türkiye had increased to 35,620. Of the existing power plants, 768 are hydroelectric, 71 are coal, 378 are wind, 66 are geothermal, 332 are natural gas, 33,545 are solar and 460 are from other sources [15].

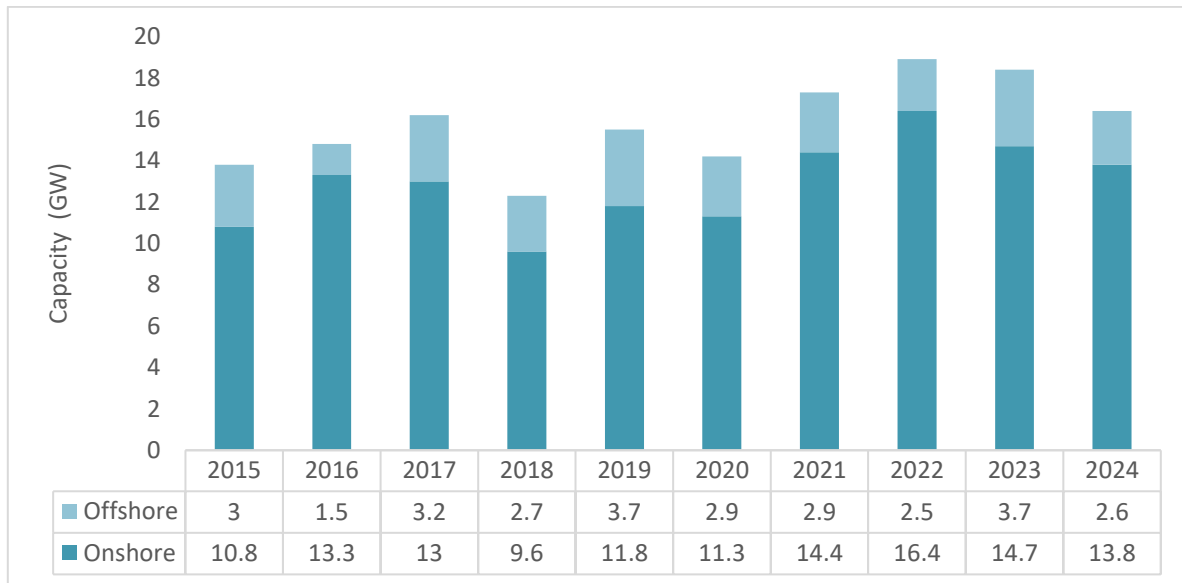


Fig. 1. Offshore and onshore distribution of the capacity generated between 2015 and 2024 [14].

In order to meet the ever-increasing energy demand, it is necessary to increase the energy obtained from renewable sources and to identify new areas for the installation of facilities. Türkiye's second largest source of renewable energy is wind energy, following hydroelectricity. A notable shift in the geographical distribution of wind power plants has been observed, with a transition from onshore to offshore locations. This transition is driven by a combination of increasing demand and mounting environmental constraints.

The selection of the most suitable site for the construction and installation of wind farms is a complex problem that depends on many factors. This requires the use of multi-criteria decision-making methods. The methods used in this field are given in the literature section.

This study aims to identify the most suitable offshore wind energy site among three potential areas within Türkiye's maritime jurisdiction, namely the offshore areas near Ayvalık, Bozcaada and Gökçeada. As a method, q-Rung Orthopair Fuzzy Sets and the COPRAS Method are used to effectively manage uncertainty and subjectivity in expert assessments.

These three alternatives were analyzed with 12 different criteria under the technical and economic, environmental and social headings. The criteria are wind speed, wave height and period, investment cost, water depth, proximity to the coast, proximity to power transmission network, vessel traffic density, proximity to military operation area, distance to fishing areas, distance to coastal tourism areas, distance to cable and pipelines, and impact on fisheries.

The second part of the paper contains a review of the extant literature on this topic. In the third part of this text, the problem definition and methodology are mentioned. The solution steps are illustrated in meticulous detail, and the results are presented for consideration. In the subsequent section, the results will be evaluated and interpreted.

2. Literature Review

For determining the most suitable locations for Offshore Wind Energy Systems (OWES) is of critical importance in terms of energy policies and sustainable development goals. In this context, the literature includes numerous studies that evaluate various methodologies and criteria related to the OWES site selection problem. This section reviews a selection of these studies, summarizing the methods employed, the factors considered, and the key findings. The aim is to reveal current research trends and the existing body of knowledge in the field, thereby highlighting how this paper contributes to literature.

Umoh et al., [17] in order to determine the most suitable locations for floating offshore wind power plants in South Africa, this study combined the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) methodologies. The aim is to make the decision-making process more systematic and transparent by considering technical, economic, environmental and social criteria. As a result, the study created suitability maps of offshore areas, ranked the most suitable locations and provided justifications for these choices, thus facilitating the planning and implementation of wind energy projects.

In their study, Dash et al., [18] utilized CRM techniques to evaluate and prioritise wind energy alternatives, incorporating a range of social, economic, environmental and technical factors. In this study, the PAPRIKA (Potentially All Pairwise Rankings of all possible Alternatives) method was utilized to evaluate wind energy systems based on key criteria, including Capacity Factor, Environmental Impact and Policy Framework. Onshore wind turbines have emerged as a viable solution due to their superior energy production and cost effectiveness (Levelized Cost of Electricity, LCOE).

Li et al., [19] presented a novel hybrid multi-criteria decision-making model, termed D-SAISM (where D signifies the use of D numbers in compressed contrastive interpretive structural modelling). The D-number method has been demonstrated to reduce uncertainties by facilitating the conversion of expert judgments into numerical data. The model combines TOPSIS and an opposite method with traditional interpretive structural modelling (ISM). The conclusion drawn from this analysis is that the effectiveness and practical utility of the proposed D SAISM model is verified when applied to a real offshore wind energy project.

Solbrekke et al., [20] the study aims to determine the most suitable wind farm areas within the Norwegian Economic Zone (NEZ) in order to reach the 30 GW offshore wind energy capacity that Norway aims to reach by 2040. For this purpose, spatial planning was carried out using the Multi-Criteria Decision Analysis (MCDA) method AHP and environmental, technical, economic and social criteria were evaluated in a multi-dimensional manner. The areas off the southern coast of Norway, especially the North Sea and Skagerrak, stand out as the most suitable areas in terms of all criteria.

Martinez et al., [21] combines GIS and multi-criteria decision-making techniques for the economic evaluation of potential regions for OWF installations, providing a systematic and applicable method to determine economically suitable areas for offshore wind energy projects.

Önden et al., [22] utilized a combination of Geographic Information System (GIS) and Multi-Criteria Decision Making (MCDM) methodologies to ascertain the optimal locations for floating offshore wind power plants, with the objective of meeting the energy demands of the railway sector in Türkiye. The Heuristic Fuzzy Weighted Average (IFWA) and Global Fuzzy Progressive Weight Rating

Ratio Analysis (SF-SWARA) methods were applied for the purpose of criteria weighting. The weights obtained from this process were then combined with the Einstein Operations t norm technique. The study concluded that the most suitable location for offshore wind power plants is the Izmir region.

Faraggiana et al., [23] in the study, in order to determine the most suitable locations of floating offshore wind power plants for the islands in the Mediterranean region, WAM was used to determine the importance of the criteria and assign weights, Fuzzy Analysis was used to make decisions by considering the uncertainties in certain criteria, TOPSIS was used to determine the alternatives that are close to the most ideal solution, and AHP was used for decision makers to determine the importance level for each criterion. The most efficient regions for floating wind power plants were determined as the areas where the wind speed is the highest and the sea depth is suitable for the installation of the plant.

Ziamba [24] this study is used for the fuzzy MCDM assessment of offshore wind energy projects planned in the Baltic Sea Economic Zone of Poland, taking into account their uncertainties and risks. To increase the reliability of the results, sensitivity and robustness analyses are performed with Monte Carlo simulations.

Hou et al., [25] proposes a methodological framework for environmental, technical, social and economic criteria to determine the most suitable locations for OWFs around the island of Crete. The most suitable areas for OWF were determined using GIS and the criteria were weighted using the AHP method.

In their seminal study, Gkeka-Serpetsidaki et al., [26] presented a systematic study combining GIS and AHP methods to assess the offshore wind energy potential of the island of Crete. The central aim of the study was twofold: firstly, to promote energy independence and, secondly, to reduce land use conflicts.

Liu and et al., [27] the use of various methods such as AHP, TOPSIS, ELECTRE, PROMETHEE, fuzzy logic and game theory, which govern this process covering the literature between 2010 and 2020 used in offshore wind energy investments, has been mentioned. It has been shown that researchers have turned to hybrid approaches instead of a single method and thus decision processes have become more robust and flexible.

De Salvo et al., [28] By analyzing the social acceptance of wind energy projects and the public's preferences towards these projects, it investigated the potential conflict between protecting the local environment and reducing greenhouse gas emissions. It was emphasized that in order for wind energy projects to be successfully implemented, public preferences and social sensitivities should be integrated into decision-making processes in addition to technical competence.

Table 1
 Overview of the studies on fuzzy MCDM with OWES

Title	Type	Method	Year	Base
Combined AHP-GIS methodology for floating offshore wind site selection in South Africa	HYBRID	AHP-GIS	2025	Scopus
Evaluating sustainable wind energy sources with multiple criteria decision-making (MCDM) techniques	-	PAPRIKA	2025	Scopus

Title	Type	Method	Year	Base
Offshore wind turbine selection with multi-criteria decision-making techniques involving D numbers and squeeze adversarial interpretive structural modeling method	HYBRID	D-SAISM	2024	Scopus

Table 1
Continued

Title	Type	Method	Year	Base
Norwegian Offshore Wind Power— Spatial Planning Using Multi-Criteria Decision Analysis	-	AHP	2024	Scopus
Economic Assessment of Potential Zones for Offshore Wind Energy: A Methodology	HYBRID	MCDM-GIS	2024	Scopus
Strategic Location Analysis for Offshore Wind Farms to Sustainably Fulfill Railway Energy Demand in Turkey	HYBRID	MCDM-GIS IFWA and SF-SWARA	2024	Scopus
Optimal Floating Offshore Wind Farms for Mediterranean Islands	HYBRID	WAM, Fuzzy Analysis, TOPSIS, AHP	2024	Scopus
Uncertain Multi-Criteria Analysis of Offshore Wind Farms Projects Investments—Case Study of the Polish Economic Zone of the Baltic Sea	HYBRID	Fuzzy MCDM and Monte Carlo Simulation	2022	Scopus
A review on recent risk assessment methodologies of offshore wind turbine foundations	HYBRID	GIS-AHP	2022	Scopus
A methodological framework for optimal siting of offshore wind farms: A case study on the island of Crete	HYBRID	GIS-AHP	2022	Scopus
Decision-Making Methodologies in Offshore Wind Power Investments: A Review	HYBRID	Proposed models MCDM	2021	Scopus
Protecting the Local Landscape or Reducing Greenhouse Gas Emissions? A Study on Social Acceptance and Preferences towards the Installation of a Wind Farm	Rewiev	-	2021	Scopus

The reviewed literature reveals Table 1. the multidimensional and complex nature of the site selection problem for offshore wind energy systems. The studies demonstrate that this decision requires careful consideration of technical, economic, environmental, and social factors. Moreover, it is evident that MCDM methods and tools such as GISs are widely employed to support these

complex decisions. These trends in the literature highlight the significance of the methodology and findings presented in our study, and underscore its valuable contribution to the existing body of knowledge in this field

In the literature review phase of this study, studies conducted between 2020-2025 and within the scope of various offshore wind farm site selection criteria were used. Some of the criteria obtained from the studies conducted between the specified periods are given in Table 2.

Table 2

Some of the criteria obtained from the studies conducted between 2020 and 2025.

Criteria/Reference	Shao et al., [29]	Diaz and Soares, [30]	Xu et al., [31]	Deveci et al., [3]	Deveci et al., [32]	Diaz et al., [33]	Gahramanov and Beji, [34]	Konurhan et al., [35]	Hosseinzadeh et al., [36]	Barzekar et al., [37]	Cali et al., [38]	Umoh et al., [17]	Dimitriou et al., [39]	Shao et al., [40]	Majidi et al., [41]	Criteria Type
Wind Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Benefit
Wave Height and Period	x			x	x				x	x	x			x	x	Cost
Investment Cost	x			x	x			x			x					Cost
Water Depth	x	x		x	x	x	x	x	x	x	x	x	x	x	x	Cost
Proximity to Shore	x	x		x	x				x	x	x	x	x	x	x	Benefit
Proximity to Power Transmission Grid	x		x	x	x	x		x	x		x	x		x	x	Benefit
Ship Traffic Density	x	x		x			x	x		x		x				Cost
Proximity to Military Operation Area	x	x		x			x			x			x			Cost
Distance from Fishing Areas	x	x								x				x		Benefit
Distance from Coastal Touristic Areas	x	x					x	x						x		Benefit
Distance from Cables and Pipelines	x	x					x	x				x				Benefit
Impact on Fisheries	x				x		x				x					Cost

3. Methodology

3.1 Problem Definition

The globally increasing demand for renewable energy has brought offshore wind power to the forefront due to its sustainability and high energy generation potential. With its long coastline and favorable wind conditions, Türkiye holds a strategic advantage for investments in this field. However, the development of OWFs is a complex process that involves high costs, long-term investment planning, and comprehensive site selection analyses.

Selecting the most suitable location for an offshore wind power plant is a MCDM problem that requires the simultaneous consideration of various technical, environmental, economic, and social factors. In the specific context of Türkiye, where offshore wind energy is still in its early stages of development, the rational and systematic evaluation of potential sites is of critical importance for ensuring investment efficiency and maximizing energy output.

This study aims to determine the most appropriate offshore wind power site among three potential areas located within Türkiye's maritime jurisdiction: offshore regions near Ayvalık, Bozcaada, and Gökçeada. To effectively manage uncertainty and subjectivity in expert evaluations, the Q-rung orthopair fuzzy set-based COPRAS method is employed. This approach enhances the

reliability and robustness of the decision-making process by enabling more flexible modeling of uncertainty.

The primary goal of the study is to identify the most suitable location among the three alternatives. The findings are expected to provide strategic insights for policymakers and investors, supporting the effective development of renewable energy investments in Türkiye. The decision-making approach of the study is presented in Figure 2.

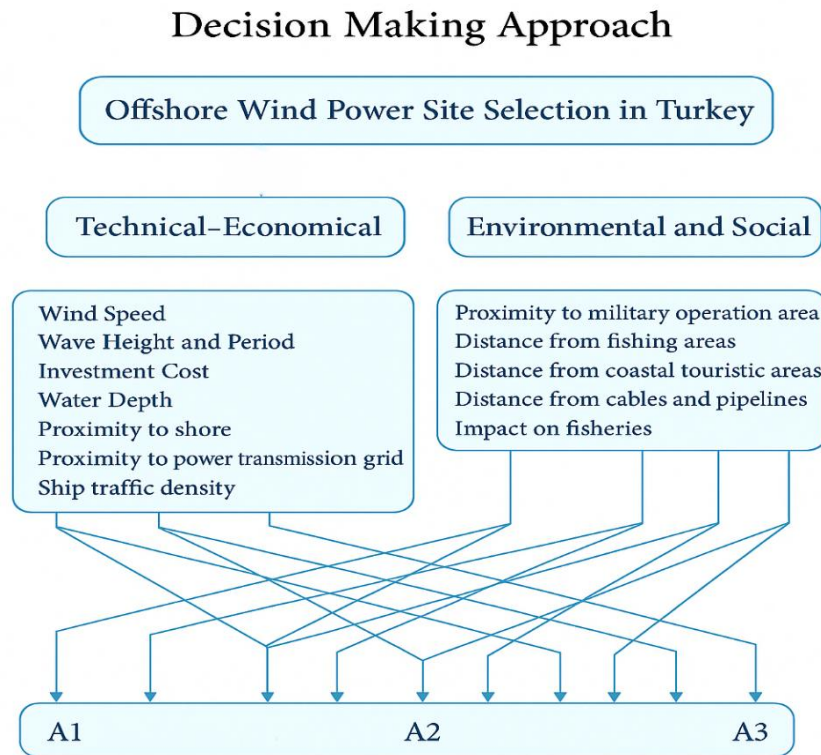


Fig. 2. Decision making approach

3.1.1 Definition of alternatives

The definition of alternatives is explained in the following:

A1: Bozcaada Offshore is a suitable region for the installation of offshore wind energy power plants due to its high wind potential and moderately deep seabed. The average wave height in the area ranges between 1.0 and 2.0 meters. The site is approximately 5 km from the shore, and connection to the mainland and the electricity grid is feasible through Çanakkale. However, the region experiences heavy maritime traffic due to its proximity to international shipping routes leading to the Istanbul Strait, and its closeness to military restricted zones may complicate permitting processes. Also, traditional fishing activities are widespread in the area. Considering all these factors, the region has significant wind energy potential but also faces certain land-use constraints [42].

A2: Gökçeada Offshore is one of the regions in Türkiye where the highest wind speeds have been recorded [3]. The sea depth in the area generally exceeds 60 meters, which necessitates the consideration of floating platform systems. The wave height ranges between 1.5 and 2.5 meters, making the area highly suitable for offshore conditions. The site is approximately 10 km from the shore, and since the island lacks sufficient electrical infrastructure, additional investments are required to establish grid connections to the mainland. Although maritime traffic is less intense compared to Bozcaada, there is a partial overlap risk with military security zones. Fishing activities

are more limited, and there is a low risk associated with existing pipeline or cable infrastructure. Due to the high wind yield, the energy production capacity is strong; however, the investment costs may be higher because of installation challenges and infrastructure requirements [42].

A3: Ayvalık Offshore offers a cost-effective opportunity for OWF installation due to its shallow waters with depths ranging from 20 to 30 meters and its proximity to the shore, approximately 5 km away. Although the average wind speed is lower compared to the other two alternatives, the lower investment costs can partially compensate for this disadvantage. Wave height is relatively low, between 0.5 and 2.0 meters. Connection to the electricity grid is possible via Balıkesir. The risk of restrictions due to maritime traffic or proximity to military zones is relatively low. However, since Ayvalık is one of Türkiye's major fishing regions, there is a high potential for interaction with fishing activities. There are no significant obstacles related to pipelines or cable routes. Despite its lower wind potential, this alternative stands out due to its shallow depth and ease of infrastructure access.

3.1.2 Definition of criteria

Technical-Economical Criteria:

C₁: Wind Speed (benefit): Average wind speed is a critical parameter in determining the technical suitability and economic efficiency of areas where OWFs will be installed. Since the kinetic energy of the wind is proportional to the cube of the wind speed, the energy production capacity is directly related to this speed [38]. As the average wind speed increases, energy production increases and the unit cost decreases; therefore, this criterion is a benefit type evaluation criterion [40].

In the literature, areas with an average wind speed below 6 m/s are considered unsuitable for commercial-scale wind energy investments and are typically excluded from evaluations [3, 17]. Therefore, when identifying suitable locations, the impact of average wind speed on both technical performance and economic feasibility should be carefully taken into account [43, 44].

C₂: Wave Height and Period (cost): Wave height and period are key factors in the site selection of OWFs, particularly in terms of structural integrity, installation/investment costs, and operational safety. Severe wave conditions can affect the stability of turbine foundations and hinder maintenance access, thereby increasing operational expenses.

Diaz et al., [33] the dynamic effects of wave conditions on turbine structures were examined, highlighting that long wave periods may elevate the risk of structural resonance. Similarly, Barzehkar et al., [37] evaluated the impact of wave loads on floating platforms, emphasizing that wave period plays a decisive role in platform stability and energy production efficiency.

Hosseinzadeh et al., [36] also noted that wave height and period are essential factors that should be incorporated into MCDM processes for OWF site selection. In this context, wave height and period should be considered as cost-type criteria in OWF site selection, since higher values can increase structural risks and operational challenges, ultimately raising the overall project cost.

C₃: Investment Cost (cost): The installation of OWFs requires highly capital investment, making investment cost one of the most fundamental economic criteria to consider during site selection. This criterion encompasses a range of components, including infrastructure investments like seabed preparation, foundations, cabling, and grid connections, turbine installation, as well as transportation and installation equipment [3, 38]. Investment costs may vary considerably based on the physical and geographical attributes of a given site. Environmental challenges such as deep waters, hard sea beds, or long distances from shore can increase costs, while favorable infrastructure and shallow waters may offer cost advantages [40]. Moreover, the magnitude of investment costs directly influences the project's payback period and overall economic feasibility [39].

In the literature, investment cost is commonly classified as a cost-type criterion. Within this framework, lower-cost alternatives are typically prioritized in decision-making processes [17].

C₄: Water Depth (cost): One of the most significant environmental parameters affecting the feasibility of OWFs is water depth. This criterion is directly related to the selected turbine technology, as fixed-bottom turbines are typically preferred in shallower waters, while deeper areas require floating platform technologies [3, 33]. As the depth increases, both the infrastructure requirements and installation costs rise substantially. In particular, for floating systems, depth plays a critical role in determining the stabilizing elements of the platform and the length of the seabed-anchored ropes, making it crucial for technological design and cost estimation [32]. Furthermore, the bathymetric structure of the selected area not only affects technical suitability but also represents a significant constraint in terms of sustainability and feasibility [33]. Studies conducted on Türkiye's Western Black Sea coast show that water depths of up to 50 meters are suitable for fixed-bottom systems, while some coastal areas with low wind speeds are unsuitable for such installations [34].

C₅: Proximity to Shore (benefit): The proximity to shore plays a critical role in both the technical and economic aspects of OWF site selection. Logistics processes, such as the transportation of materials and equipment during installation and the transmission of generated electricity to the shore, can be carried out more efficiently in areas closer to the coast [35]. Therefore, areas near the shore are typically prioritized for evaluation due to their lower installation and maintenance costs [38]. However, wind farms located too close to the shore may have negative effects on human activities, such as visual pollution, noise, and water sports, which could lead to the exclusion of areas within a certain distance limit [37]. For example, marine planning approaches in some countries state that areas within 10 km of the shore are not suitable for wind farm installations. Although this criterion requires a multidimensional evaluation in terms of environmental and social acceptability, in this study, it will be examined within the context of the technical-economical main criterion.

C₆: Proximity to Power Transmission Grid (benefit): The geographical distribution of OWFs is typically characterized by their distance from areas with high population density and significant electricity demand. Consequently, the design of transmission networks must be such that they facilitate the transfer of power from OWFs over long distances [3]. The electricity generated by OWFs is economically valuable only when it reaches the offshore substation and end consumers. Consequently, OWFs must be in close proximity to local electricity and power transmission networks [6].

C₇: Ship Traffic Density (cost): Ship traffic density is an important factor in the site selection of OWFs, as it directly impacts both safety and operational feasibility. High-density shipping routes increase the risk of accidents and interference during the construction and operation of OWFs. Therefore, a proper safety buffer zone is required between wind farms and shipping lanes to mitigate these risks. For instance, a minimum safety distance of 2 nautical miles is recommended between the outer boundary of an OWF and shipping lanes [45]. Additionally, safety zones should be expanded to at least 5 nautical miles at the entry and exit points of traffic separation schemes, and a minimum of 4 nautical miles from anchorage areas [34]. Low-traffic marine areas are preferred for wind farm locations to reduce potential risks and ensure the safety of both the wind farm and marine traffic [46].

Environmental and Social Criteria:

C₈: Proximity to Military Operation Area (cost): When selecting sites for OWFs, the proximity to areas used by naval forces for military operations must be carefully considered. Locations actively used for periodic or special military activities are generally deemed unsuitable for OWFs development [3]. Military forbidden zones and their surrounding areas are critical limitations in the

planning of OWF sites. For instance, in the western Black Sea region of Türkiye, a second-degree military forbidden zone has been established near the coast, with a recommended additional buffer zone of 3 kilometers to avoid interference with military radars and operations [34]. The European Marine Spatial Planning Platform (2019) suggests maintaining a minimum distance of 500 meters between military zones and offshore wind projects, although greater distances are considered preferable for enhanced safety and operational efficiency [37]. Therefore, ensuring sufficient distance from military operation areas is essential both for national security and for the sustainable operation of OWFs.

C₉: Distance from Fishing Areas (benefit): OWFs can disturb marine ecosystems, particularly affecting fish populations through underwater noise, and could lead to a reduction in fishing activities and fish production. Therefore, maintaining an adequate distance from major fishing areas is crucial to minimizing conflicts with the fishing sector [7]. OWFs are generally required to avoid regions of intense fishing activity, especially areas dominated by trawling, the most common fishing method in Europe [47]. According to international regulations such as the United Nations Convention on the Law of the Sea, a 500-meter buffer zone is typically established around offshore wind turbines and associated infrastructure, where fishing activities are often restricted [47]. In the North Sea, several countries enforce this exclusion zone to safeguard both fisheries and offshore energy operations. Moreover, this criterion is considered a cost criterion, where greater distances indicate a lower potential impact on fisheries [48, 40]. Thus, careful site selection that respects appropriate separation from fishing grounds is essential to ensure the coexistence of offshore energy development and marine resource sustainability.

C₁₀: Distance from Coastal Touristic Areas (benefit): OWFs must consider their potential impact on coastal tourism, including activities like beach visits, yacht tours, boat excursions, diving, etc. Wind turbines placed near popular tourist destinations may reduce the aesthetic and recreational value of these areas due to visual and noise disturbances [35]. Studies indicate that the negative perception of OWFs by tourists decreases with increasing distance from the shore, highlighting the importance of locating turbines farther offshore to mitigate these effects [49]. This criterion serves as a benefit criterion to evaluate this impact; greater distances correlate with lower adverse effects.

C₁₁: Distance from Cables and Pipelines (benefit): The development of OWFs must take into account the presence of existing underwater infrastructure, such as energy transmission and communication lines. Due to its strategic and geographical location, Türkiye hosts several critical subsea cable networks, serving both as a transit route and for national needs. For example, the Black Sea Fiber Optic System, which connects Romania, Bulgaria, and Türkiye through the Black Sea, can be mentioned. While parts of this system, such as the segment near İğneada, overlap with restricted military zones, other sections are located farther offshore and present fewer constraints for wind farm siting. Ensuring sufficient distance from underwater cables and pipelines is crucial to prevent physical damage, facilitate maintenance activities, and avoid operational conflicts. Consequently, OWFs must be planned with appropriate buffer zones around such infrastructures to ensure the safe coexistence of both energy and communication systems.

C₁₂: Impact on Fisheries (cost): The impact on fisheries refers to potential affects to fishing activities during the construction and operation of OWFs. These impacts may include displacement of fishing grounds, restrictions on vessel navigation, a reduction in fish populations due to habitat changes, and economic losses for fishing communities. The evaluation of this impact typically involves factors such as the economic value of the affected fisheries, the number of small-scale fishing boats operating in the area and expert assessments of the ecological and socio-economic importance of

the fisheries. Minimizing conflicts with fishing activities is crucial to ensure the sustainable coexistence of offshore energy projects and traditional marine livelihoods.

3.2 Preliminaries

The theory of fuzzy logic was invented by Dr. Lotfi Aliasker Zadeh in 1965. The basis of the theory is that the old Aristotelian logic does not give complete and precise results but instead uses fuzzy sets and fuzzy numbers to solve problems frequently encountered in daily life more clearly. Although the concept of fuzzy logic in its simplest form, such as "a little cold", "very weak", "very fast", "a little wrong", does not have a mathematical meaning, it is seen as a system that can be used to solve many problems. It also forms the basis of the operation of devices used in daily life in a way that people can understand [50].

The application areas of fuzzy logic are very wide. Its biggest benefit is that it allows the "human-specific learning through experience" phenomenon to be easily modeled and that even vague concepts can be expressed mathematically. For this reason, it is particularly suitable for approaching nonlinear systems [51].

3.2.1 Comparison of q-ROF sets with Pythagorean and other fuzzy sets

In the Pythagorean fuzzy set proposed by Yager [52] The degrees of membership and non-membership are indicated as (μ, γ) , such that $\mu, \gamma \in [0, 1]$ and this situation is expressed by Eq. (1).

$$\mu^2 + \gamma^2 \leq 1 \quad (1)$$

$\mu = T_p(a)$ is the membership degree and $\gamma = T_n(a)$ is the non-membership degree of a in T . Also, $\mu^2 + \gamma^2 = r^2$

In q-ROF, T is expressed by Eq. (2).

$$T = \{(a, \mu_T(a), \gamma_T(a)) | a \in U\} \quad (2)$$

The following conditions in Eq. (3). are met: μ_T is the membership degree and γ_T is the non-membership degree.

$$(\mu_T(a))^q + (\gamma_T(a))^q \leq 1 \quad (3)$$

The hesitation index is defined as $\pi_T(a) = (1 - ((\mu_T(a))^q + (\gamma_T(a))^q))^{1/q}$

Figure 3 shows that Pythagorean fuzzy sets (PFS) have a larger solution set than intuitionistic fuzzy sets (IFS). All IFS membership degrees μ and γ can also be expressed as PFS membership degrees. However, some IFS membership degrees cannot be expressed as PFS [52].

The best example of this is when the membership degrees (0.8; 0.6) are used, if it is expressed as IFS, $0.8 + 0.6 = 1.4$, and the IFS does not satisfy the condition $\mu + \gamma \leq 1$. When PFS is used, since $0.8^2 + 0.6^2 = 0.64 + 0.36 = 1$, the condition $\mu^2 + \gamma^2 \leq 1$

The value of q can be infinite and at infinite it becomes graphically square. Operations with q-ROF numbers are shown below [53].

Intersection: Let C and D be q-rung fuzzy numbers. Membership and non-membership degrees of these numbers are presented by Eq. (4) and Eq. (5):

$$C(a) = \{a, (\mu_C(a))^q, (\gamma_C(a))^q | a \in U\} \quad (4)$$

$$D(a) = \{a, (\mu_D(a))^q, (\gamma_D(a))^q | a \in U\} \quad (5)$$

Strength of dependence S of both fuzzy numbers is defined by Eq. (6).

$$(\mu_C(a))^q + (\gamma_C(a))^q = S_C \leq 1, (\mu_D(a))^q + (\gamma_D(a))^q = S_D \leq 1 \quad (6)$$

Let the intersection of fuzzy sets C and D be in Eq. (7). $I = C \cap D$:

$$I(a) = \{a, (\mu_I(a))^q, (\gamma_I(a))^q | a \in U\} \quad (7)$$

The intersection sets are given by Eq. (8) and Eq. (9).

$$(\mu_I(a))^q = \text{Min}\{(\mu_C(a))^q, (\mu_D(a))^q\} \quad (8)$$

$$(\gamma_I(\alpha))^q = \text{Min}\{(\gamma_C(\alpha))^q, (\gamma_D(\alpha))^q\} \tag{9}$$

For I to be a q-rung fuzzy number, $(m_I(\alpha))^q + (\gamma_I(\alpha))^q \leq 1$ must be satisfied.

Union: Similarly, unity is defined as $U = C \cup D$ and is shown in Eq. (10) and Eq.(11).

$$Y(\alpha) = \{\alpha, (m_Y(\alpha))^q, (\gamma_Y(\alpha))^q \mid \alpha \in U\}$$

$$(m_Y(\alpha))^q = \text{Min}\{((m_C(\alpha))^q, (m_D(\alpha))^q)\} \tag{10}$$

$$(\gamma_Y(\alpha))^q = \text{Min}\{((\gamma_C(\alpha))^q, (\gamma_D(\alpha))^q)\} \tag{11}$$

Coverage: For the coverage to be $C(\alpha) \cap D(\alpha)$ in q-rung fuzzy sets,

$$(m_C(\alpha))^q \geq (m_D(\alpha))^q \wedge (\gamma_C(\alpha))^q \leq (\gamma_D(\alpha))^q \text{ condition must be satisfied.}$$

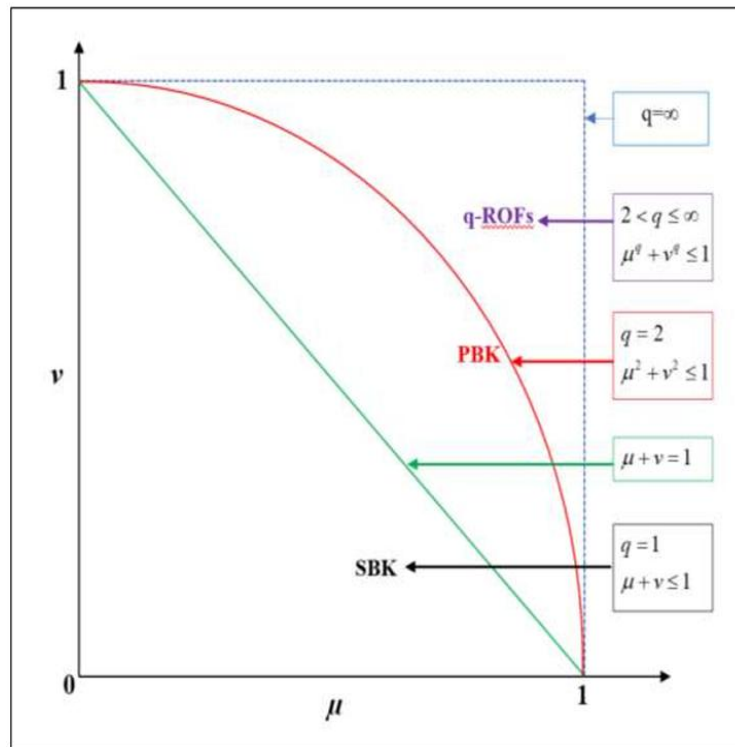


Fig. 3. Comparison of fuzzy sets

3.2.1.1 q-ROF aggregation operators

After Yager [53] defined the aggregation functions in q-rung fuzzy sets, many aggregation operators were defined. The q-ROFWA and q-ROFWG aggregation operators defined by Liu and Wang [54] are generally accepted in the literature. These aggregation operators are used in this article.

Weighted Aggregation Operator:

Let $\theta_g = \langle m_g, \gamma_g \rangle (g = 1, 2, \dots, s)$ be a q-ROF number.

$$q-ROFWA(\theta_1, \theta_2, \dots, \theta_s) = \Omega_1 \theta_1 \oplus \Omega_2 \theta_2 \oplus \dots \oplus \Omega_s \theta_s$$

$$0 \leq \Omega_g \leq 1 \text{ and } \sum_{g=1}^s \Omega_g = 1, \text{ weight vector of } (\theta_1, \theta_2, \dots, \theta_s) \text{ is } \Omega = (\Omega_1, \Omega_2, \dots, \Omega_s)^T.$$

The ultimate equation of the q-ROF weighted aggregation operator is shown in Eq. (12).

$$q-ROFWA(\theta_1, \theta_2, \dots, \theta_s) = \langle \left(1 - \prod_{g=1}^s (1 - m_g^q)^{\Omega_g} \right)^{\frac{1}{q}}, \sum_{g=1}^s \gamma_g^{\Omega_g} \rangle \tag{12}$$

The q-ROF geometric weighted aggregation operator is shown by Eq. (13).

$$q-ROFWG(\theta_1, \theta_2, \dots, \theta_s) = \langle \prod_{g=1}^s m_g^{\Omega_g}, \left(1 - \prod_{g=1}^s (1 - \gamma_g^q)^{\Omega_g} \right)^{\frac{1}{q}} \rangle \tag{13}$$

$$q-ROFWG(\theta_1, \theta_2, \dots, \theta_s) = \theta_1^{\Omega_1} \otimes \theta_2^{\Omega_2} \otimes \dots \otimes \theta_s^{\Omega_s}$$

$$0 \leq \Omega_g \leq 1 \text{ and } \sum_{g=1}^s \Omega_g = 1, \text{ weight vector of } (\theta_1, \theta_2, \dots, \theta_s) \text{ is } \Omega = (\Omega_1, \Omega_2, \dots, \Omega_s)^T$$

3.2.1.2 q-ROF score and accuracy functions

$\theta_g = \langle \eta_g, \gamma_g \rangle (g = 1, 2, \dots, s)$ is a q-ROF number.

The score function is defined by Eq. (14)

The accuracy function is presented by Eq. (15)

$$S(\theta) = \frac{1 + \eta(\alpha)^q - \gamma(\alpha)^q}{2} \tag{14}$$

$$h(\theta) = \eta(\alpha)^q + \gamma(\alpha)^q \tag{15}$$

3.2.2 Q-rung Orthopair fuzzy COPRAS methodology

Figure 4 shows the algorithm of the application.

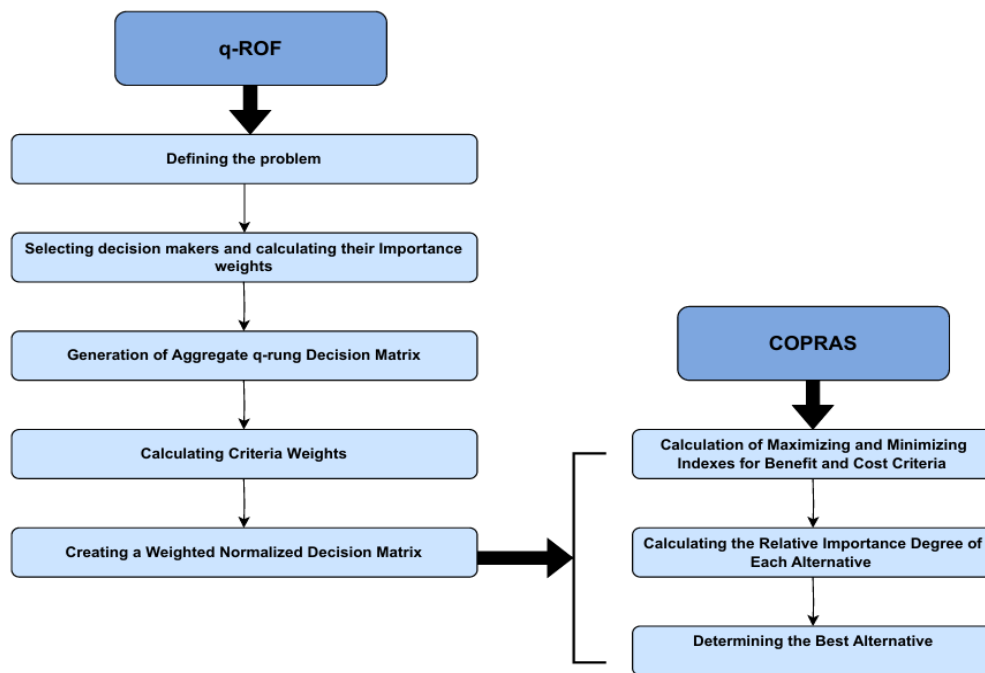


Fig. 4. Q-rung Orthopair fuzzy COPRAS algorithm

Step 1. Selecting Decision Makers and Calculating Their Importance Weights

After the problem is defined, decision makers are selected. Let the set of alternatives be $X = \{X_1, X_2, X_3, \dots, X_n\}$ and criteria set be expressed as $Z = \{Z_1, Z_2, Z_3, \dots, Z_n\}$.

First, decision makers are evaluated in linguistic terms using the seven scales shown in Table 3.

Table 3
 Table of q-ROW linguistic terms [55]

Linguistic terms	Abbreviations	η	γ
Extremely high	EH	0.95	0.15
Very high	VH	0.85	0.25
High	H	0.75	0.35
Medium high	MH	0.65	0.45
Medium	M	0.55	0.55
Medium low	ML	0.45	0.65
Low	L	0.35	0.75
Very low	VL	0.25	0.85
Extremely low	EL	0.15	0.95

$M_g = [m_g(\alpha), \nu_g(\alpha), \tau_g(\alpha)]$ is a q-ROF number that is rated to evaluate the importance of each decision maker and q is the level of the q-rung Orthopair fuzzy set.

Eq. (16) is used to rate the kth decision makers' importance weight.

$$\Omega_g = \frac{1+m_g^q - \nu_g^q}{\sum_{g=1}^p (1+m_g^q - \nu_g^q)} \quad (16)$$

$$\sum_{g=1}^p \Omega_g = 1 \text{ and } g = 1, 2, 3, \dots, p$$

Step 2. Building Aggregated q-ROF Decision Matrix

Decision makers rate alternatives. These evaluations are then converted into q-ROF numbers to create a matrix.

Eq. (12) is used to create the collective decision matrix. It is envisaged that decision makers' importance weights will also be considered in the calculation of the equation.

Step 3: Determining Criteria Importance Weights

After the decision makers evaluate the criteria for each alternative, these evaluations are converted into q-ROF numbers using Eq. (17).

$$\varphi_j = \frac{\sum_{g=1}^p \Omega_g (1+m_{jg}^q - \nu_{jg}^q)}{\sum_{j=1}^s \sum_{g=1}^p (1+m_{jg}^q - \nu_{jg}^q)} \quad (17)$$

$$\varphi = \{\varphi_1, \varphi_2, \varphi_3, \dots, \varphi_s\}, \quad \text{and } \sum_{j=1}^s \varphi_j = 1$$

Step 4. Creating Normalized Weighted Decision Matrix

The creation of the normalized weighted decision matrix is implemented by multiplying the elements in the aggregated decision matrix with the importance weights of the criteria, as shown in Eq. (18).

$$\varphi_g \theta_1 = \langle (1 - (1 - m_1^q)^{\varphi_g})^{\frac{1}{q}}, \nu_1^{\varphi_g}, \tau_{Ai}(\alpha_j) = (1 - m_{Ai}^q(\alpha_j) - \nu_{Ai}^q(\alpha_j)^{1/q} \rangle \quad (18)$$

$r'_{ij} = (m'_{ij}, \nu'_{ij}, \tau'_{ij}) = [m_{Ai} \varphi(\alpha_j), \nu_{Ai} \varphi(\alpha_j), \tau_{Ai} \varphi(\alpha_j)] \quad i = 1, 2, 3, \dots, z; j = 1, 2, 3, \dots, s$ is an element of the aggregated weighted q-ROF decision matrix (R').

Step 5. Calculation of Maximization and Minimization Indexes Each Type of Criterion

Benefit criteria and cost criteria are evaluated separately. Our aim is to maximize benefit criteria and minimize cost criteria. According to the method, benefit criteria are aggregated and called P_i .

r'_{ij}^+ represents the criteria to be maximized and are the values of the R' matrix. P_i is calculated by Eq. (19).

$$P_i = \sum_{j=1}^g r'_{ij}^+, \quad i = 1, 2, 3, \dots, z \quad (19)$$

Then the cost criteria to be minimized are aggregated and calculated as the R_i value with Eq. (20). Similarly, here r'_{ij}^- are the values to be minimized in the R' matrix.

$$R_i = \sum_{j=g+1}^s r'_{ij}^-, \quad i = 1, 2, 3, \dots, z \quad (20)$$

First, the P_i and R_i values are calculated as q-ROF numbers, then they are defuzzified using the score function shown in Eq. (21).

$$S(A) = \frac{1+m(\alpha)^q - \nu(\alpha)^q}{2} \quad (21)$$

Step 6: Calculating the Relative Importance of Each Alternative with Eq. (22).

$$Q_i = P_i + \frac{R_{min} \sum_{j=1}^z R_i}{R_i \sum_{j=1}^z \frac{R_{min}}{R_i}} \quad (22)$$

Step 7: Ranking the Best Alternatives by Calculating Their Utility Values with Eq. (23).

$$N_i = \left(\frac{Q_j}{Q_{max}} \right) * 100 \tag{23}$$

The alternatives are ranked from largest to smallest.

3.3 Application of the q-rung Orthopair Fuzzy Sets-Based Site Selection for Offshore Wind Power Plant Installation Project in Turkish Maritime Regions

The COPRAS MCDM method based on q-rung Orthopair fuzzy sets was used to determine the location selection of the offshore wind power plant project within the Turkish maritime jurisdiction areas. Twelve criteria were used in the application. 6 of them are benefit criteria and the other 6 are cost criteria. Three alternative locations for the wind power plant project were used as Bozcaada offshore, Gökçeada offshore and Ayvalık offshore. In addition, 3 decision-makers who are experts in this field evaluated all criteria according to each alternative and the weight of each criterion in linguistic terms.

3.3.1 Experimental results

Using the q-ROF COPRAS methodology, the ranking of alternatives for offshore wind power plant project installation site selection is described by the following steps.

Step 1. Selecting Decision Makers and Calculating Their Importance Weights

After defining the problem, 3 decision makers from Türkiye who are experts in offshore wind power plants were selected and assigned to evaluate the criteria. Then, the decision makers were evaluated in linguistic terms according to their experience in the field of expertise and importance. Weights were calculated using Eq. (16) and are presented in Table 4.

Table 4
DM Importance Weights

DM	Rating	η_j	γ_j	DM weights
Ω_1	EH	0,95	0,15	0,364
Ω_2	EH	0,95	0,15	0,364
Ω_3	H	0,75	0,35	0,271

Step 2. Building Aggregated q-ROF Decision Matrix

The determined criteria were evaluated by decision makers according to each alternative. The linguistic terms were used in the evaluation and shown in Table 5. These evaluations were changed to q-ROF numbers using Eq. (12) and presented in Table 6.

Table 5
Decision Makers' Evaluation of Criteria in Linguistic Terms

Main Criteria	Sub Criteria/Alternatives	A1	A2	A3	
DM1	Wind Speed	EH	EH	H	
	Wave Height and Period	H	H	MH	
	Technical- Economical Criteria	Investment Cost	H	VH	H
		Water Depth	ML	H	MH
		Proximity to shore	VH	H	VH
		Proximity to power transmission grid	VH	H	H
	Environmental- Social Criteria	Ship traffic density	H	H	MH
		Proximity to military operation area	MH	MH	M
		Distance from fishing areas	M	MH	L
		Distance from coastal touristic areas	VH	VH	VH
Distance from cables and pipelines		M	MH	MH	
Impact on fisheries		H	MH	EH	

Table 5
 Continued

Main Criteria	Sub Criteria/Alternatives	A1	A2	A3		
DM2	Technical- Economical Criteria	Wind Speed	EH	VH	VH	
		Wave Height and Period	H	H	MH	
		Investment Cost	VH	VH	H	
		Water Depth	H	EH	H	
		Proximity to shore	H	H	H	
		Proximity to power transmission grid	VH	H	H	
		Ship traffic density	VH	H	MH	
	Environmental- Social Criteria	Proximity to military operation area	H	H	MH	
		Distance from fishing areas	VH	VH	H	
		Distance from coastal touristic areas	H	H	VH	
		Distance from cables and pipelines	MH	MH	MH	
		Impact on fisheries	VH	H	EH	
		Main Criteria	Sub Criteria/Alternatives	A1	A2	A3
		DM3	Technical- Economical Criteria	Wind Speed	EH	H
Wave Height and Period	H			H	MH	
Investment Cost	VH			VH	VH	
Water Depth	H			VH	H	
Proximity to shore	VH			H	VH	
Proximity to power transmission grid	VH			VH	H	
Ship traffic density	VH			MH	MH	
Environmental- Social Criteria	Proximity to military operation area		M	H	H	
	Distance from fishing areas		H	H	M	
	Distance from coastal touristic areas		MH	H	H	
	Distance from cables and pipelines		MH	MH	MH	
	Impact on fisheries		H	MH	H	

Table 6
 Aggregated q-ROF Decision Matrix

Criteria/Alternatives	A1			A2			A3		
	η	γ	τ	η	γ	τ	η	γ	τ
C11. Wind Speed	0.9499	0.1500	0.5187	0.8881	0.2274	0.6602	0.7943	0.3096	0.7771
C12. Wave Height and Period	0.7498	0.3500	0.8121	0.7500	0.3500	0.8119	0.6500	0.4500	0.8592
C13. Investment Cost	0.8206	0.2826	0.7518	0.8500	0.2500	0.7181	0.7840	0.3195	0.7860
C14. Water Depth	0.6826	0.4386	0.8423	0.8832	0.2346	0.6681	0.7192	0.3836	0.8299
C15. Proximity to shore	0.8206	0.2826	0.7518	0.7500	0.3500	0.8119	0.8207	0.2826	0.7516
C16. Proximity to power transmission grid	0.8498	0.2500	0.7183	0.7840	0.3195	0.7860	0.7500	0.3500	0.8119
C17. Ship traffic density	0.8206	0.2826	0.7518	0.7276	0.3747	0.8253	0.6500	0.4500	0.8592
C21. Proximity to military operation area	0.6740	0.4336	0.8491	0.7192	0.3836	0.8299	0.6561	0.4523	0.8550
C22. Distance from fishing areas	0.7545	0.3650	0.8051	0.7709	0.3393	0.7952	0.6152	0.5223	0.8549
C23. Distance from coastal touristic areas	0.7770	0.3314	0.7908	0.7943	0.3096	0.7771	0.8289	0.2739	0.7429
C24. Distance from cables and pipelines	0.6186	0.4841	0.8662	0.6500	0.4500	0.8592	0.6500	0.4500	0.8592
C25. Impact on fisheries	0.7941	0.3096	0.7773	0.6926	0.4106	0.8428	0.9250	0.1887	0.5865

Step 3: Determining Criteria Weights

Eq. (17) was used to calculate the importance of weights of the criteria and is visualized in Table 7.

Table 7
 Criteria Importance Weights

Criteria	DM1	DM2	DM3	Weights
C11. Wind Speed	EH	EH	EH	0.092661
C12. Wave Height and Period	VH	EH	VH	0.084712
C13. Investment Cost	H	VH	VH	0.076059
C14. Water Depth	EH	VH	EH	0.088007
C15. Proximity to shore	VH	EH	VH	0.084712
C16. Proximity to power transmission grid	VH	VH	EH	0.083353
C17. Ship traffic density	EH	EH	H	0.086761
C21. Proximity to military operation area	H	VH	VH	0.076059
C22. Distance from fishing areas	VH	VH	VH	0.080058
C23. Distance from coastal touristic areas	EH	EH	VH	0.089366
C24. Distance from cables and pipelines	VH	VH	VH	0.080058
C25. Impact on fisheries	VH	VH	VH	0.080058

Step 4. Building Normalized Weighted Decision Matrix

The aggregated matrix and criterion weights are calculated using Eq. (18) to create the normalized weighted decision matrix and are shown in Table 8.

Table 8
 Normalized Weighted Decision Matrix

Criteria/Alternatives	A1			A2			A3		
	η_j	γ_j	τ_j	η_j	γ_j	τ_j	η_j	γ_j	τ_j
C11. Wind Speed	0.5484	0.8388	0.6256	0.4728	0.8717	0.6143	0.3966	0.8971	0.5998
C12. Wave Height and Period	0.3565	0.9149	0.5737	0.3566	0.9149	0.5737	0.2994	0.9346	0.5393
C13. Investment Cost	0.3900	0.9084	0.5761	0.4119	0.8999	0.5861	0.3654	0.9169	0.5651
C14. Water Depth	0.3212	0.9300	0.5456	0.4605	0.8802	0.6040	0.3423	0.9191	0.5682
C15. Proximity to shore	0.4038	0.8985	0.5933	0.3566	0.9149	0.5737	0.4039	0.8985	0.5932
C16. Proximity to power transmission grid	0.4240	0.8909	0.6007	0.3764	0.9093	0.5798	0.3548	0.9162	0.5711
C17. Ship traffic density	0.4069	0.8962	0.5971	0.3457	0.9184	0.5689	0.3017	0.9331	0.5431
C21. Proximity to military operation area	0.3016	0.9384	0.5268	0.3264	0.9297	0.5447	0.2921	0.9414	0.5201
C22. Distance from fishing areas	0.3529	0.9225	0.5551	0.3631	0.9171	0.5654	0.2759	0.9493	0.4979
C23. Distance from coastal touristic areas	0.3803	0.9060	0.5860	0.3920	0.9005	0.5939	0.4171	0.8907	0.6044
C24. Distance from cables and pipelines	0.2776	0.9436	0.5174	0.2939	0.9381	0.5303	0.2939	0.9381	0.5303
C25. Impact on fisheries	0.3782	0.9104	0.5762	0.3168	0.9312	0.5436	0.4905	0.8750	0.5963

Step 5. Calculation of Maximization and Minimization Indexes for Benefit and Cost type criteria

Criteria C11 Wind Speed, C15 Proximity to Shore, C16 Proximity to Power Transmission Grid, C22 Distance from Fishing Areas, C23 Distance from Coastal Touristic Areas and C24 Distance from Cables and Pipelines are benefit criteria, C12 Wave Height and Period, C13 Investment Cost, C14 Water Depth, C17 Ship Traffic Density, C21 Proximity to Military Operation Area and C25 Impact on Fisheries are cost criteria. According to the characteristics of the criteria, P_i and R_i values were found by using Eq. (4.19) and (4.20) respectively, and according to these values, the score values were calculated with Eq. (4.21) as shown in Table 9.

Table 9
 P_i and R_i score values

Alternatives	P_i	R_i
A1. Bozcaada Offshore	0.679936	0.623096
A2. Gokceada Offshore	0.644858	0.637633
A3. Ayvalık Offshore	0.625754	0.622966

Step 6-7: Calculate the Relative Importance for Each Alternative (Q_i) and Ranking the Best Alternatives by Calculating Their Utility Values (N_i)

Q_i and N_i values were found using Eq. (22) and (23), respectively, and the final values for evaluating the alternatives are given in Table 10.

Table 10
 Relative significance and utility degrees

Alternatives	Q_i	N_i	Ranking
A1. Bozcaada Offshore	1.246	100.000	1
A2. Gokceada Offshore	1.198	96.149	2
A3. Ayvalık Offshore	1.192	95.661	3

3.3.2 Comparison analysis

To check the accuracy of the q-ROF COPRAS process, a comparison analysis was performed using the q-ROF TOPSIS process and q-ROF WASPAS process. It is seen that all three methods give the same results at the time of comparison. The best alternative was determined as the first Bozcaada offshore, the second Gökçeada offshore and finally the worst alternative was determined as the Ayvalık offshore. The final results of the comparative analysis are shown in Table 11.

Table 11
 Ultimate Results of the Comparative Analysis

Alternatives/ Methods	q-ROF COPRAS		q-ROF TOPSIS		q-ROF WASPAS	
	N_i	Ranking	Proximity to the ideal solution	Ranking	WASPAS Score	Ranking
A1. Bozcaada Offshore	100	1	0.739281172	1	0.05747384	1
A2. Gokceada Offshore	96.14907	2	0.580700682	2	0.04750167	2
A3. Ayvalık Offshore	95.66122	3	0.450184076	3	0.02098504	3

3.3.3 Sensitivity analysis

In order to check the sensitivity of the results for q-ROF COPRAS and other methods, evaluations were made by increasing the q level. As a result of the evaluation of the alternatives, the results of all three methods do not change as Bozcaada, Gökçeada and Ayvalık in the section of q level up to 25. When q level is greater than 25, there is a change in q-ROF WASPAS method and the alternatives are listed as Gökçeada, Bozcaada, Ayvalık. When q level reaches 37, there is a change in q-ROF TOPSIS method, and it catches the same order with q-ROW WASPAS. In the q-ROF COPRAS method, the order of the alternatives does not change at any level of q. This situation is shown in Table 12.

Table 12
 Ultimate Results of the Sensitivity Analysis

Methods	q-ROF COPRAS			q-ROF TOPSIS			q-ROF WASPAS		
	A1. Bozcaada Offshore	A2. Gökçeada Offshore	A3. Ayvalık Offshore	A1. Bozcaada Offshore	A2. Gökçeada Offshore	A3. Ayvalık Offshore	A1. Bozcaada Offshore	A2. Gökçeada Offshore	A3. Ayvalık Offshore
q=3	100	96.1491	95.6612	0.73928	0.5807	0.45018	0.057474	0.047502	0.02099
	1	2	3	1	2	3	1	2	3
q=10	100	96.2711	95.4495	0.86082	0.77914	0.61207	0.371365	0.362366	0.32086
	1	2	3	1	2	3	1	2	3
q=20	100	97.9024	97.1864	0.91959	0.88771	0.74499	0.58814	0.585969	0.55013
	1	2	3	1	2	3	1	2	3
q=26	100	98.5664	98.0223	0.93964	0.92428	0.79525	0.651582	0.651589	0.62252
	1	2	3	1	2	3	2	1	3
q=36	100	99.221	98.9008	0.96252	0.96175	0.86055	0.706427	0.707793	0.68889
	1	2	3	1	2	3	2	1	3
q=37	100	99.2656	98.9624	0.96429	0.96435	0.86611	0.709794	0.711202	0.69316
	1	2	3	2	1	3	2	1	3
q=50	100	99.6488	99.5003	0.98137	0.98608	0.92398	0.735586	0.736894	0.72744
	1	2	3	2	1	3	2	1	3
q=70	100	99.88	99.8294	0.99343	0.99674	0.97118	0.746818	0.747437	0.74422
	1	2	3	2	1	3	2	1	3
q=90	100	99.9577	99.94	0.99774	0.99913	0.98972	0.749251	0.749479	0.74843
	1	2	3	2	1	3	2	1	3
q=100	100	99.9748	99.9643	0.99869	0.99952	0.99392	0.74963	0.749763	0.74917
	1	2	3	2	1	3	2	1	3

When q level approaches 100, the score points of the alternatives start to approach each other and when q level reaches infinity, all score values in each method become equal. When Yager [53] introduced this method, he particularly emphasized that q can be increased to infinity and that when it reaches infinity, the solution set will form a square shape.

In Figure 5, the sensitivity analysis of q-ROF COPRAS method and spider plots consisting of 10 levels for each of the three alternatives are plotted. It is seen that there is no change in the ranking of Bozcaada Offshore (A1) criterion for all values of q levels and the rankings of Gökçeada Offshore (A2) and Ayvalık Offshore (A3) remain constant with the change of q levels. This shows that the q-ROF COPRAS method is insensitive to the variability of q levels.

The spider plot for the sensitivity analysis of the q-ROF WASPAS method is shown in Figure 6. As the q level increases, the alternative values also increase, and when the q level reaches 26, the Gökçeada Offshore (A2) alternative surpasses the Bozcaada Offshore (A1) alternative and reaches the best position.

The spider plot for the sensitivity analysis of the q-ROF TOPSIS method is shown in Figure 7. In this method, it is seen that the Gökçeada Offshore (A2) alternative becomes the best alternative in case the q level is changed and exceeds 37.

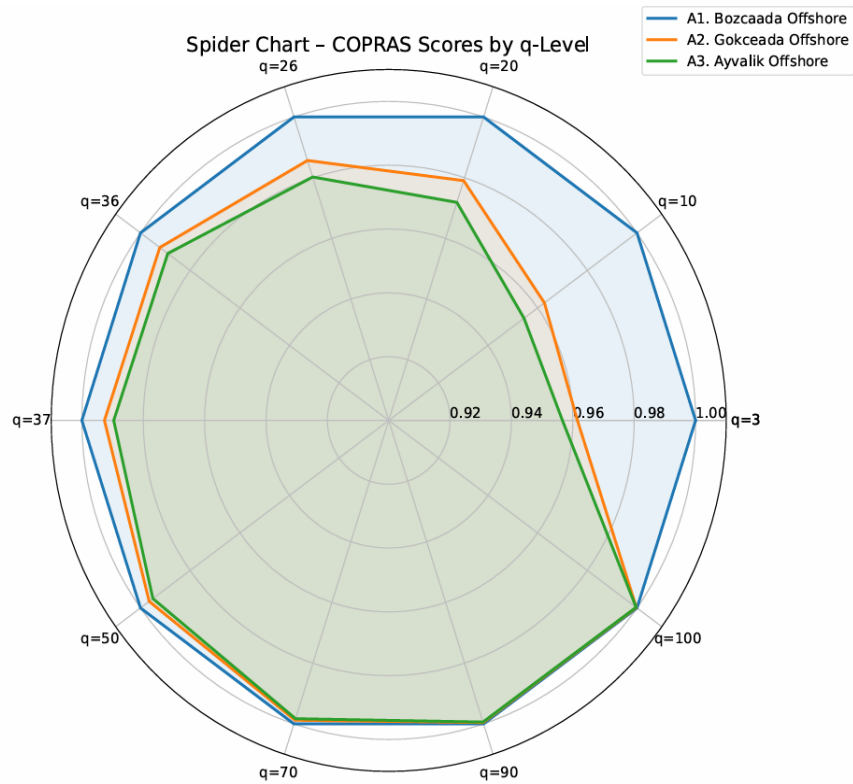


Fig. 5. q-rung Orthopair Fuzzy COPRAS Sensitivity Analysis

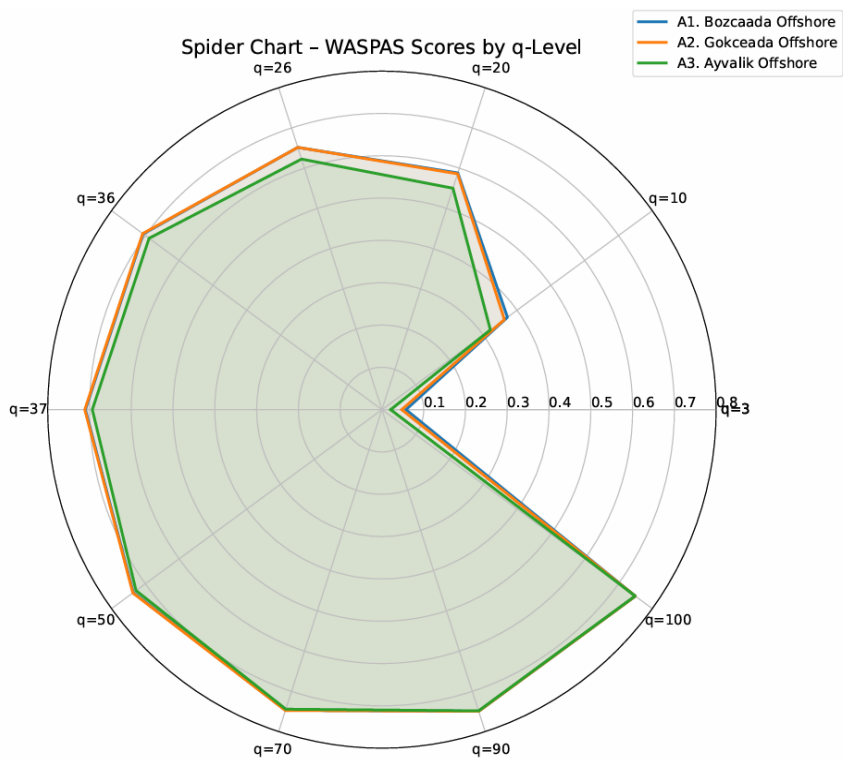


Fig. 6. q-rung Orthopair Fuzzy WASPAS Sensitivity Analysis

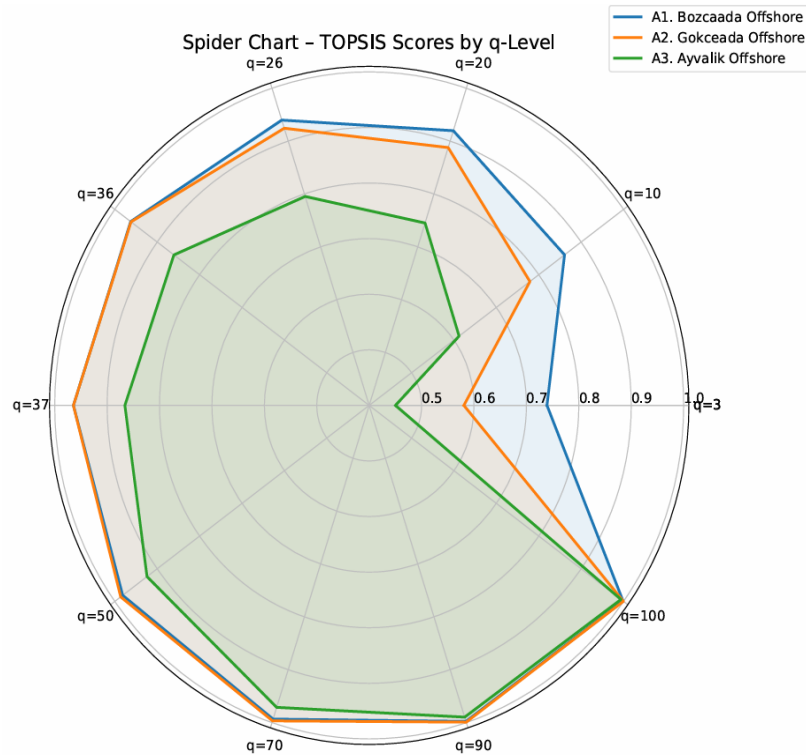


Fig. 7. q-rung Orthopair Fuzzy WASPAS Sensitivity Analysis

According to all three methods, Ayvalık Offshore (A3) remains the worst alternative, its ranking unchanged at all q levels.

4. Conclusions

In this study, it is aimed to select the location of offshore wind power plant within the maritime jurisdiction areas of Türkiye. The alternatives are Ayvalık, Bozcaada, and Gökçeada. For this purpose, in order to represent uncertainties Q-rung Orthopair fuzzy set (q-ROFS) and as the MCDM method COPRAS is used.

Firstly, twelve criteria obtained as a result of literature research were evaluated by three different experts. While determining these criteria, attention was paid to finding criteria that would fall within the scope of technical, strategic, social and environmental criteria, also inspired by the literature.

According to the results of the COPRAS method requested for the Experimental Results step, the alternatives were ranked as A1 (Bozcaada) > A2 (Gökçeada) > A3 (Ayvalık). This result shows that, according to the determined criteria and decision makers' evaluations, Bozcaada Offshore is more suitable than Gökçeada Offshore and Gökçeada Offshore is more suitable than Ayvalık Offshore.

These results were compared with the results obtained with the TOPSIS and WASPAS methods and the same ranking was obtained. Finally, sensitivity analysis was performed based on the change of the q value. In the sensitivity analysis stage, the same results were observed up to a certain q value level.

To further elaborate this study, the same problem can be addressed with different fuzzy approaches and the outputs can be examined. Also, different MCDM methods can be used.

This study conducted for the Aegean Sea can be expanded and implemented for the Black Sea and the Mediterranean Sea with the support of decision makers. In this case, it will be necessary to review the criteria differences that may arise due to the different characteristics of the seas in question.

Author Contributions

Conceptualization, J.G., B.G.; introduction, Ş.D.; literature search, M.K.B., B.G.; methodology, J.G., B.G.; analysis, J.G.; evaluation of results, A.T.; writing, J.G., B.G., A.T., M.K.B., Ş.D.; review and editing, J.G., B.G., A.T., M.K.B., Ş.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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

Data Availability Statement

The datasets generated during and/or analyzed during the current study is available from the corresponding author on reasonable request.

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