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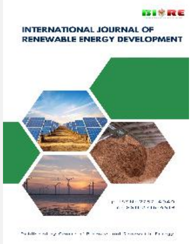

Review Article

An integrated interval-valued q-Rung Orthopair fuzzy DEMATEL–Choquet integral framework for prioritizing investment drivers of green energy in marine sector: A case study in Vietnam

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Abstract. With the rising demand for energy, the commitments to decarbonization and international regulations in the marine sector, the move towards sustainable maritime energy systems has become a strategic priority for Vietnam. It is thus important to understand what the most important investment drivers are in order to help with evidence-based policy development and effective resource allocation. This study aims to build an integrated framework using interval-valued q-rung orthopair fuzzy (IVq-ROF) DEMATEL and Choquet Integral methods to assess and prioritize the fourteen investment criteria that affect Vietnam's maritime energy economy. The expert judgements were gathered using the IVq-ROF linguistic assessment framework, which is used to capture uncertainty and interdependence between the criteria. DEMATEL method was used to identify causal relationships and the importance of the evaluation criteria, and the Choquet integral was used to include the interaction effects to arrive at final importance weights. The results show that three top investment priorities are the government incentives and financial support (0.095), the port energy infrastructure readiness (0.085) and compliance with IMO and national regulations (0.084). Stakeholder acceptance (0.046) and skilled workforce availability (0.054) have comparatively lower interaction adjusted importance, respectively. DEMATEL causal analysis identified port energy infrastructure investment cost (C1) as the strongest driving factor (highest D−R), whereas the interaction-aware Choquet ranking identified government incentives and financial support (0.095), port energy infrastructure readiness (0.085), and compliance with IMO and national regulations (0.084) as the three highest overall investment priorities. The proposed framework well reflects the linkages between economic, technical, environmental, regulatory, and social aspects and offers guidance for practical implementation of the maritime energy transition in Vietnam through integrated investment planning and sustainable infrastructure development to achieve the transition faster.

Keywords: Maritime; Green energy; Energy economy; Decarbonization; MCDM; IVq-ROF DEMATEL

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1. Introduction

The worldwide maritime transportation trade is at a significant operational and environmental juncture, directly impacted by the new IMO greenhouse gas (GHG) regulatory strategy that aims for net-zero emissions by or about 2050 (Dzida & Nguyen, 2026; Hoang *et al.*, 2022; H. P. Nguyen *et al.*, 2021). The sweeping decarbonization mandate calls for a complete revolution of the global maritie energy economy and represents a sudden technical and financial challenge to coastal countries (Do, Nguyen, *et al.*, 2026; Domachowski, 2021; Pham *et al.*, 2023) This structural shift poses significant institutional challenges as well as high-stakes capital investment decisions to rapidly developing maritime countries such as Vietnam, where a long coastline of over 3260 km is a central trade route in Southeast Asia (Ghoneim *et al.*, 2023; Kanrak *et al.*, 2026). This re-engineering of a country's maritime energy system needs to be coordinated and involve investment in port facilities, domestic shipping fleets, and regional fuel supply chains. In recent years, the deployment of the green port concept and framework is considered a potential strategy to achieve decarbonization and net-zero goals in the maritime sector in Vietnam (Dinh *et al.*, 2025; Do, Le, *et al.*, 2026; H. P. Nguyen, Nguyen, *et al.*, 2022; H. P. Nguyen, Pham, *et al.*, 2022). In addition, policymakers and port authorities must make difficult technical choices with competing factors regarding economic feasibility, technological readiness, life cycle environmental effects, and social and political acceptability (V. N. Nguyen *et al.*, 2023; Yalama *et al.*, 2022) Choices for strategic capital investments can be made between shore-side power infrastructure investments (Alternative Maritime Power), bunkering infrastructure for alternative marine fuels (such as green methanol, green ammonia, or green hydrogen), or smart port microgrids, and can be viewed as a multi-criteria decision-making (MCDM) problem with a high level of uncertainty and many interconnected risk factors (Dang & Nguyen, 2025; Dinh *et al.*, 2024; Erdem & Akyuz, 2021; Hoang *et al.*, 2023; Le *et al.*, 2023; Lee *et al.*, 2025; Soner *et al.*, 2017a).

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In the literature, Wu *et al.* (Wu *et al.*, 2022) reported that research on maritime decarbonization and the transition towards greener ports has also been rapidly increasing, as scientists assess the viability of improved ship design, alternative fuels, and sustainable port operations. Ma et al. (Ma et al., 2026) reported that initial studies focused on the cost economics of conventional liquefied natural gas (LNG) bunkering, a transitional fuel; however, recent research highlights that only zero-carbon or 'net-zero' alternative fuels will meet the IMO 2050 targets (S. Nguyen *et al.*, 2025). Researchers have been keen on the assessment of the life cycle emissions of various options and technical challenges. For example, Venltayel A et al. (Amat Ventayol *et al.*, 2025) has investigated comparative life cycle assessment of fuel cell and hydrogen-powered engines for shipping. The study concluded that hydrogen can help to reduce GHG emissions by almost 84%. In other such energy assessment studies by Koilo V (Koilo, 2024) and Ha et al. (Ha *et al.*, 2026) have recently been conducted, showing that liquefied or compressed hydrogen has smaller volume constraints than green methanol and green ammonia, but has specific technical and safety issues. Hoang et al. (Hoang *et al.*, 2026) in their extensive review reported that Methanol is highly compatible with existing marine engine designs.

The use of MCDM methodologies is an indispensable tool to systematically assess these multifaceted variables in the realm of maritime energy economics (Do *et al.*, 2025; Duc & Nguyen, 2025; L. H. Nguyen & Nguyen, 2025). The Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) have often been applied in traditional approaches to rank alternative marine fuels and assess green shipping corridors (Celik & Akyuz, 2018a; Md Arof, 2015; Putra *et al.*, 2023; Sudjono *et al.*, 2025; Tekeli *et al.*, 2024; Tsioufis *et al.*, 2024). For example, classical hybrid MCDM models have been used to evaluate the alternatives of clean fuels based on the shipping companies' point of view, considering the installation cost and the stability of the fuel cost (Kołakowski *et al.*, 2024; Sevim & Zincir, 2025). But with the increasing volatility of the decision-making environment, researchers have been using more and more fuzzy set theories to model the subjective, vague, and incomplete information associated with emerging technologies (Bilgen *et al.*, 2025; V.-S. Nguyen & Im, 2019; Tran, 2020). The progress of fuzzy MCDM has been made from traditional fuzzy sets to intuitionistic fuzzy sets (Atanassov, 1986) and Pythagorean fuzzy sets (Khan *et al.*, 2023), which may help to model the uncertainty of the expert judgments by using different membership and non-membership.

Although these mathematical developments are present, there are three important gaps in the literature: The first restriction that is required in the conventional maritime MCDM applications is the independence of the criteria. Conventional weighting methods are based on the assumption that evaluation dimensions are independent and that there is a linear hierarchy of dimensions (J. Liu *et al.*, 2023; Stanković *et al.*, 2021). In the real world of the maritime sector, criteria are closely interdependent with each other, as the availability of green financing, for instance, has a direct impact on retrofit feasibility, which is a technical criterion, while the carbon price, for example, is a policy criterion that dynamically affects the environmental lifecycle target (Altınpınar, 2025; Hamid-Mosaku *et al.*, 2024). Failure to account for such cross-dependencies and feedback systemically biases the decision model and may result in unrealistic ranking outcomes (Alshibani *et al.*, 2026; Y. Zhang & Lu, 2025). Second, the existing models are not well suited to deal with epistemic uncertainty in the assessment of early-stage technologies. However, the maritime energy transition has limited historical data, making it difficult to rely on objective data, and expert panels often rely on subjective opinion. Advanced forms of fuzzy sets, such as Fermatean fuzzy sets, have greater evaluation spaces, but they are not mathematically flexible enough to express at any point in time the hesitation, membership, and non-membership of an expert on complex choices without being constrained by boundaries (Koilo, 2025; Suárez de Vivero & Rodríguez Mateos, 2012). The above limitation is overcome by Interval Valued q-Rung Orthopair Fuzzy Sets (IVq-ROFSs), which represent the membership grades as intervals, and their decision space can be expanded dynamically according to the complexity of the problem (P. Liu & Wang, 2018; Naz *et al.*, 2024). Also, most of the comprehensive maritime energy investment frameworks reported in the literature are for developed, high-income European and East Asian economies with well-developed capital markets and technical infrastructure. The research

Table 1
Summary of published studies in maritime MCDM domain.

Source	Application and decision method	Main limitation	Research gap addressed by this study
Kandakoglu *et al.* (Kandakoglu *et al.*, 2009)	Shipping registry selection, SWOT–AHP–TOPSIS	Assumes independent evaluation criteria and linear weighting; does not model uncertainty or feedback relationships.	Develops an interaction-aware framework that captures causal dependencies and uncertainty simultaneously.
Soner *et al.* (Soner *et al.*, 2017b)	Maritime transportation decision-making, Interval Type-2 Fuzzy AHP–VIKOR	Considers fuzzy uncertainty but lacks interaction-aware weighting and criterion synergy analysis.	Integrates causal analysis with non-additive Choquet aggregation to account for interactions among criteria.
Çelik and Akyüz (Celik & Akyuz, 2018b)	Ship loader selection, Interval Type-2 Fuzzy AHP–TOPSIS	Focuses on ranking alternatives without analysing causal relationships among evaluation criteria.	Simultaneously evaluates causal influence, systemic importance, and interaction-adjusted priorities.
Ren and Liang (Ren & Liang, 2017)	Sustainable marine fuel selection, Fuzzy Logarithmic Least Squares + Fuzzy TOPSIS	Models uncertainty but assumes additive weighting and ignores interdependencies among criteria.	Employs IVq-ROF DEMATEL–Choquet Integral to incorporate uncertainty, causal influence, and criterion interactions.
Moshiul *et al.* (2023)	Alternative marine fuel selection, TOPSIS-based MCDM	Provides alternative ranking but does not consider causal relationships or interaction effects among criteria.	Introduces interaction-aware weighting and causal network analysis for investment prioritization.
Present Study	Green energy investment prioritization in Vietnam's maritime sector, IVq-ROF DEMATEL–Choquet Integral	—	Develops a localized evaluation hierarchy for Vietnam and proposes an interaction-aware framework that simultaneously models interval uncertainty, causal relationships, non-additive criterion interactions, and policy-oriented investment prioritization.

conducted is very limited in nature and lacks a local focus on the specific economic, institutional, and operational contexts of developing maritime economies such as Vietnam. Vietnam's maritime industry is bound by capital constraints, tied to state-owned enterprises, and is dealing with two challenges: fast-growing port capacity and international decarbonization requirements. Table 1 summarizes the previously published important maritime MCDM studies.

The present endeavor is designed to fill the gaps of the identified literature. It intends to offer an interaction-aware decision-support framework for maritime green energy investment under uncertainty. The proposed framework has three methodological advancements compared with the existing hybrid studies of MCDM, which mostly contain the combination of fuzzy DEMATEL and aggregation operators. It first constructs a localized evaluation hierarchy, which consists of six dimensions and 14 criteria specially designed for Vietnam's maritime energy sector based on a literature review and expert validation. Second, it combines IVq-ROF DEMATEL with Choquet Integral in a sequential framework to overcome the criterion independence assumption and simultaneously account for uncertainty, causal relationships, and interaction effects. Third, it differentiates causal drivers, systemic prominence, and interaction-adjusted priorities, and offers more substantial decision insights and implemented investment advice for nascent maritime economies.

The present study makes three main contributions to the literature: (i) A localized evaluation framework is developed: The Vietnam maritime energy transition is evaluated by a hierarchy of six dimensions and fourteen investment criteria, which are derived from literature and validated by experts, (ii). Weighting framework based on interaction: The proposed IVq-ROF DEMATEL–Choquet Integral approach considers uncertainty, causal relationships and interactions among criteria to produce more realistic priority weights compared to traditional independent weighting techniques, (iii). Greater information and policy relevance for maritime investment planning: The framework allows separating causal influences, systemic importance and interaction adjusted priorities for greater policy and information for maritime investment planning.

2. Methodology

2.1 Criteria assessment

The evaluation criteria used in this study have been carefully chosen after a thorough literature review on maritime energy, sustainable transportation, energy economics, and maritime decarbonization and validated by domain experts. An extensive literature survey initially identified a larger pool (19) of potential evaluation indicators. After removing overlapping and low-relevance indicators and conducting expert validation, the final fourteen criteria were retained because they collectively provide a balanced representation of the economic, energy, environmental, technical, policy, and social dimensions relevant to Vietnam's maritime energy transition. Fourteen criteria were then categorized into six primary dimensions: economic, energy, environmental, technical, policy and regulatory, and social aspects to comprehensively assess the investment priorities for Vietnam's maritime energy economy (see Table 2). The economic dimension (C1–C3) assesses the financial viability of investments in maritime energy, taking into account the investment cost of infrastructure, the return on investment and the presence of green financing mechanisms. These are important criteria to evaluate long-term economic viability, as most maritime energy projects involve large capital investments. The energy dimension (C4–C6) assesses the energy efficiency of proposed investments, access to low-carbon marine fuels, and the increase in national maritime

Table 2
Criteria and description for green energy in maritime sector

Dimension	Code	Evaluation Criterion	Description
Economic	C1	Port energy infrastructure investment cost	Capital investment required for implementing maritime energy infrastructure (Xiao et al., 2024).
	C2	Return on investment	Expected economic benefits and financial returns over the project lifecycle (Pangalos, 2023).
	C3	Access to green maritime finance	Availability of public and private financial support, including green bonds and sustainable financing mechanisms (Chairunnisa, 2024; Gavalas, 2025).
Energy	C4	Maritime energy efficiency improvement	Potential to reduce energy consumption and improve operational efficiency (Alshareef & Alghanmi, 2024; Battaglia et al., 2024).
	C5	Availability of low-carbon marine fuels	Accessibility and long-term supply of alternative marine fuels such as green hydrogen, methanol, ammonia, LNG, and biofuels (Levikhin & Boryaev, 2025; Xing et al., 2021)
	C6	Maritime energy security	Ability to improve fuel supply reliability and reduce dependence on imported conventional fuels (Kosai & Unesaki, 2016).
Environmental	C7	Greenhouse gas emission reduction	Capability to reduce CO_2 and other greenhouse gas emissions throughout maritime operations (IMO, 2021).
	C8	Environmental sustainability	Contribution to minimizing environmental impacts, including air pollution and ecological degradation (Mansouri et al., 2015).
Technical	C9	Technology maturity	Readiness and commercial viability of the proposed investment technology (Wagner, 2025).
	C10	Port energy infrastructure readiness	Availability and adequacy of supporting infrastructure, including bunkering, shore power, storage, and grid connectivity (Wei et al., 2023).
Policy and Regulatory	C11	Government incentives and financial support	Availability of policy incentives, subsidies, tax benefits, and investment support for maritime energy projects (Anwar & Li, 2021).
	C12	Compliance with IMO and national regulations	Alignment with IMO decarbonization targets and Vietnam's maritime and energy policies (Le et al., 2023; UNCTAD, 2023).
Social	C13	Skilled workforce availability	Availability of trained personnel for operation, maintenance, and management of advanced maritime energy technologies (Raphael, 2025; Sbitenkova, 2024)
	C14	Stakeholder acceptance	Support from shipping companies, port authorities, investors, policymakers, and local communities for implementing maritime energy investments (Kumar & Yadav, 2026; Satta et al., 2025).

Table 3
Background of expert used in this study

Stakeholder Category	Representative Sub-Sector / Organization Type	Invited (n)	Responded (n)	Responded ID Codes	Response Rate (%)	Mean Experience (Years)
Port Authorities	State-owned Port Operators & Port Directors	3	3	E01–E03	100%	19.0
Shipping Companies	Commercial Fleet Managers & Marine Engineers	4	3	E04–E06	75.0%	16.5
Universities	Maritime Transport & Energy Economics Professors	4	3	E07–E09	75.0%	21.5
Energy Agencies	National Energy Grid & Fuel Infrastructure Analysts	3	3	E10–E12	100%	15.0
Maritime Regulators	Ministry of Transport & Policy Enforcement Officials	3	2	E13–E14	66.7%	20.0
Renewable Energy	Green Hydrogen & Solar Infrastructure Developers	3	2	E15–E16	66.7%	13.5
Total Panel Summary	Cross-Disciplinary Evaluation Cohort	20	16	—	80.0%	17.7

energy security of the investments. These factors directly affect the future maritime energy system of Vietnam in terms of resilience and sustainability. The environmental dimension (C7 – C8) centers on the reduction of greenhouse gas emissions and the minimization of negative environmental effects, which is in line with Vietnam's ambition to reach international climate goals and achieve sustainable maritime development. The technical dimension (C9–C10) evaluates the development of emerging maritime energy solutions and the readiness of supporting infrastructure - bunkering facilities, shore power systems, storage capacity, and grid connections - that together define the practicality of alternative energy solutions. The policy and regulatory aspect (C11-C12) looks at government measures, financial support facilities, and alignment with the IMO decarbonization strategy and Vietnam's national maritime and energy policy. These criteria offer the institutional support that is needed to promote investment and speed up the process of technology uptake. Last, the social dimension (C13–C14) examines the availability of skilled human resources and the acceptance of stakeholders, because the implementation of maritime energy projects will require skilled human resources and active support from government agencies, port authorities, shipping companies, investors and the local community. These 14 criteria constitute a balanced and integrated assessment framework, reflecting the economic, technical, environmental, institutional and social factors affecting investment decisions in Vietnam's maritime energy economy, which then serve as the basis for the next step of the IVq-ROF DEMATEL–Choquet Integral analysis.

2.2 Expert background

The opinions of the experts were gathered from a panel of experts with a multidisciplinary background representing key stakeholders of the Vietnam maritime energy sector to guarantee the reliability and practical relevance of the evaluation process. Twenty experts were invited, and 16 experts completed the questionnaire for an overall return rate of 80.0%. The expert panel was composed of representatives from port authorities, shipping companies, universities, energy agencies, maritime regulatory authorities and renewable energy organizations, resulting in a well-balanced mix of technical, economic, policy and operational viewpoints (see Table 3). All the port authorities and energy agencies responded, with their highest participation (100%) indicating their active role in maritime energy planning and development of energy infrastructure facilities, followed by 75.0% from shipping companies and 75.0% from universities. Maritime regulators and developers of renewable energy had a 66.7% response rate, providing important insights into regulatory compliance and the state of renewable energy technologies. In general, the experts participating in the project had a high level of professional experience, with an average of 17.6 years, ranging from 13.5 years for renewable energy developers to 21.5 years for university professors who specialize in maritime transport and energy economics. The composition of this expert panel is diverse and well-experienced, which gives a solid basis for the IVq-ROF DEMATEL–Choquet Integral analysis and makes sure that the assessment is based on both academic knowledge and practical industry experience along the maritime energy value chain.

2.3 Interval-valued q-Rung Orthopair Fuzzy DEMATEL–Choquet integral

In this study, the Interval-Valued q-Rung Orthopair Fuzzy (IVq-ROF) DEMATEL–Choquet Integral framework is employed (Eq. (1) to Eq. (9)), combining uncertainty modeling, causal relationship analysis, and weighting mechanisms considering interactions, for prioritizing the investment criteria for Vietnam's maritime energy economy. First, linguistic variables are used to describe the expert evaluations, and these evaluations are transformed into Interval-Valued q-Rung Orthopair Fuzzy Numbers (IVq-ROFNs), which simultaneously represent the interval-valued membership and non-membership degrees and are more flexible in expressing uncertainty as compared to the conventional fuzzy environments. The linguistic evaluation scale is listed in Table 4.

An IVq-ROFN is defined as (Wan *et al*., 2023; X. Zhang *et al*., 2023):

Table 4
Linguistic evaluation scale used in the IVq-ROF DEMATEL

Linguistic term	Abbreviation	Interval-valued membership	Interval-valued non-membership
No Influence	NI	(0.00, 0.05)	(0.95, 1.00)
Low Influence	LI	(0.25, 0.35)	(0.65, 0.75)
Medium Influence	MI	(0.45, 0.55)	(0.45, 0.55)
High Influence	HI	(0.70, 0.80)	(0.20, 0.30)

$$\tilde{A} = ([\mu_L, \mu_U], [\nu_L, \nu_U]) \quad (1)$$

subject to

$$(\mu_U)^q + (\nu_U)^q \leq 1, q \geq 1 \quad (2)$$

Where: μ and ν denote the membership and non-membership intervals, respectively. In the present study, the parameter $q$was selected in accordance with recommendations reported in previous IVq-ROF studies. A larger value of $q$enlarges the feasible decision space and provides greater flexibility for representing uncertainty, hesitation, and imprecision in expert judgments than intuitionistic or Pythagorean fuzzy sets. The selected value offers an appropriate balance between uncertainty representation and computational stability, making it suitable for evaluating complex maritime energy investment criteria characterized by subjective expert assessments.

The linguistic assessments are converted into the direct-relation matrix $X = [x_{ij}]_{n\times n}$, which is normalized as:

$$N = \frac{X}{\max_i \left(\sum_{j=1}^{n} x_{ij} \right)} \quad (3)$$

The normalized matrix is subsequently used to compute the total relation matrix:

$$T = N(I - N)^{-1}, \quad (4)$$

Where: I represents the identity matrix.

The influence and dependence of each criterion are obtained by calculating the row and column sums of the total relation matrix:

$$D_i = \sum_{j=1}^{n} t_{ij}, \quad (5)$$

$$R_i = \sum_{i=1}^{n} t_{ij}. \quad (6)$$

The overall importance (prominence) and causal relationship of each criterion are determined using

$$P_i = D_i + R_i, \quad (7)$$

$$C_i = D_i - R_i \quad (8)$$

Positive (Ci) means that the criterion is in the cause group; negative means that it is in the effect group.

Following the computation of the normalized total relation matrix, the pairwise interaction indices between criteria were estimated directly from the normalized total influence values. These indices represent the overall direct and indirect influence exchanged between criteria and were subsequently incorporated into the construction of the Choquet fuzzy measure. Consequently, the Choquet Integral produces interaction-adjusted criterion weights that explicitly consider non-additive relationships among the investment criteria.

The Choquet integral is used to merge the importance weights to consider the interaction between the criteria. The discrete Choquet integral is given by (Grabisch, 1997; Marichal, 2000):

$$C_\mu(x) = \sum_{i=1}^{n} \left(x_{(i)} - x_{(i-1)} \right) \mu(A_{(i)}), \quad (9)$$

Where $x_{(i)}$denotes the ordered criterion values, $\mu(A_{(i)})$is the fuzzy measure (capacity) associated with subset $A_{(i)}$, and $x_{(0)} = 0$. The Choquet integral, unlike the usual weighted averaging, is able to explicitly depict the individual contribution of each criterion as well as the synergies or redundancies between criteria. Thus, the combined IVq-ROF DEMATEL–Choquet method offers a holistic decision support model that is able to determine the most significant investment priority factors with a sense of uncertainty, causal dependence, and interactive effects among investment factors in Vietnam's maritime energy economy. Following is the pseudo-code used for preparing Python code in this study:

Input:
Expert linguistic evaluations of the 14 investment criteria.
Step 1: Convert linguistic assessments into IVq-ROF numbers.
Step 2: Aggregate all expert judgments to construct the collective IVq-ROF direct-relation matrix.
Step 3: Defuzzify and normalize the direct-relation matrix.
Step 4: Compute the total relation matrix using the DEMATEL procedure.
Step 5: Calculate transmitted influence (D), received influence (R), prominence (D + R), and net causal effect (D − R).
Step 6: Estimate pairwise interaction strengths from the normalized total relation matrix.
Step 7: Construct the Choquet fuzzy measure using the estimated interaction information.
Step 8: Compute interaction-adjusted criterion weights using the Choquet Integral.
Step 9: Rank the investment criteria according to the fina interaction-adjusted weights.

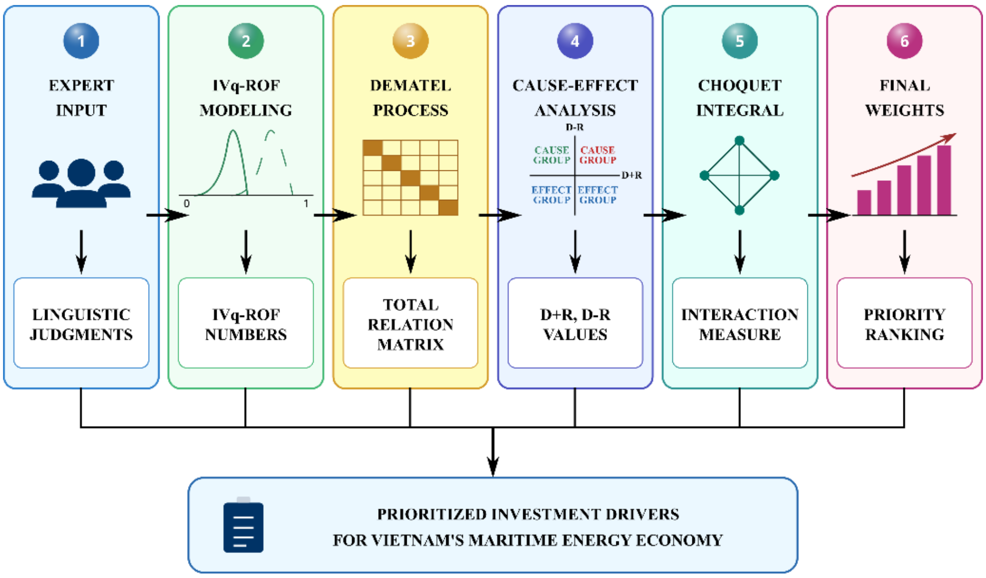


Fig. 1. Methodology flow chart

Output: Final priority ranking, causal relationships, and interaction-aware importance weights for maritime green energy investment criteria.

All computations were implemented in Python 3.11.13 using custom-developed scripts. Numerical matrix operations and data processing were performed using NumPy 2.3.2 and Pandas 2.3.1, while graphical visualizations were generated using Matplotlib 3.10.5. Fig. 1 depicts the methodology implementation in this study.

3. Results and Discussion

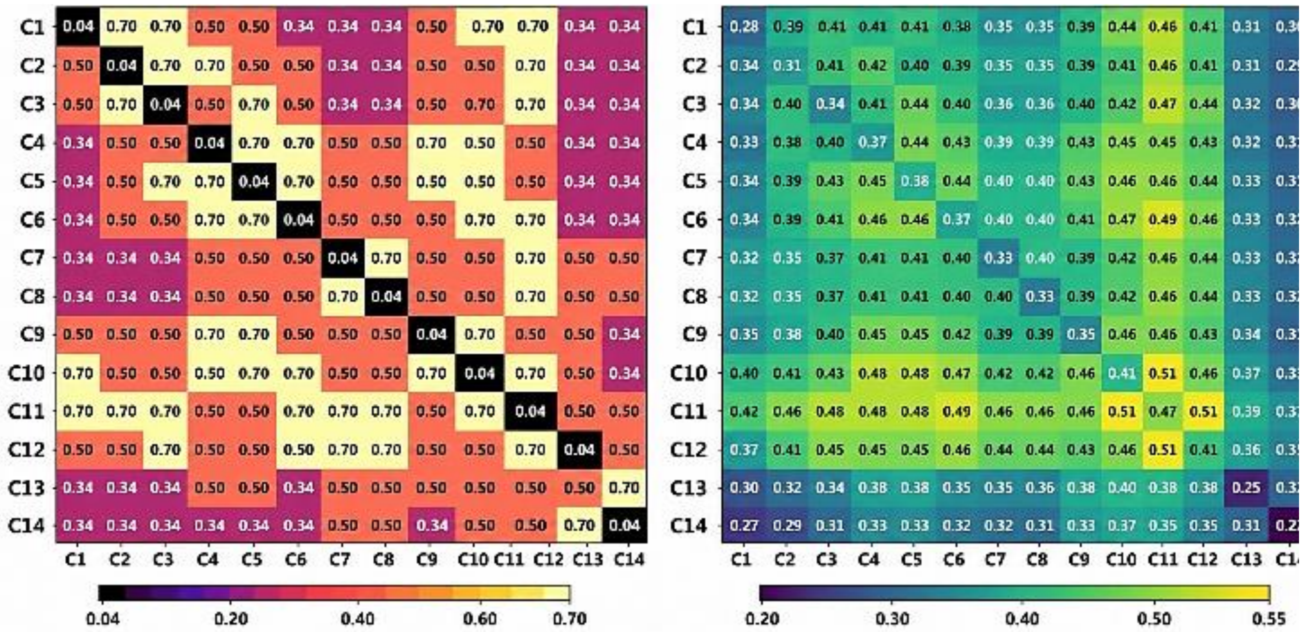
3.1 Causal Mapping and Systemic Interdependencies

A comparison of two cell-annotated numeric grids, Fig. 2(a) and Fig. 2(b), reveals the structural behavior and the evolutionary dynamics of the maritime energy investment evaluation criteria. The direct-relation matrix normalized and mapped is shown in Fig. 2(a). During this first phase, these links between the 14 criteria are distinctly separated and thus transformed into express, distinct evaluation units, which are based on the direct expert feedback. A strong self-influence control baseline of 0.04 is the main diagonal, with isolated and prominent areas of high intensity in the remainder of the matrix. The diagonal values represent the normalized self-reference values retained during aggregation rather than causal self-loops. For instance, C11 (Government incentives and financial support) has an immediate, strong direct influence score of 0.70 across several dimensions including C2 (Return on investment), C3 (Access to green maritime finance), C7 (Greenhouse gas emission reduction), C8 (Environmental sustainability) and C12 (Compliance with IMO and national regulations). In the same way, C5 (Availability of low-carbon marine fuels) shows a direct value of 0.70 for C3, C4 (Maritime energy efficiency improvement), C6 (Maritime energy security), C9 (Technology maturity) and C10 (Port energy infrastructure readiness). These values show that, at first, experts view policy interventions and fuel supply chains as stand-alone, immediate drivers of financial and technical preparedness.

After being integrated by the total fractional matrix inversion procedure, in order to resolve infinite long-range feedback cycles, this map of transmission relations (total relations) as a function of dependency indices, shown in Fig. 2(b), indicates a very continuous and non-linear dependency spectrum. When multiple indirect feedback loops are mathematically compounded, there is a general increase in scores throughout the network. This systemic propagation is accentuated by the main diagonal baseline: the self-influence of 0.04 for the cell that is influenced by itself moves with a significant jump into the active continuous range from 0.22 in the lower limit of the cell (C14, C14) to 0.38 in cell (C5, C5).

More importantly, the compounding nature results in a significant 'bunching' of structural convergence around the policy, infrastructure and compliance sub-circuit. This is explicitly verified in Figure 2(b), in which cells (C10, C11), (C11, C10) and (C11, C12) all have the maximum network value of 0.51. This highest value confirms the fact that, in full network conditions, the port readiness (C10) and regulatory compliance (C12) constitute a high leverage and close continuum of priorities and inter-dependency with the government incentive (C11). On the other hand, peripheral parameters, like C14 (Stakeholder acceptance), are visually and numerically isolated at the margins of the system with the lowest values of columns going in (e.g., 0.30 in C1 and dropping down to 0.22 at cell C14, C14). Indeed, this quantitative comparison is straightforward, and while standalone direct metrics provide entry points to the maritime energy economy, the long-range total relation matrix is needed to uncover the true high-leverage 'hotspots' that are moving Vietnam's maritime energy economy.

As shown in Fig. 3(a) and Fig. 3(b), the total direct influence (D) and the total dependence (R) of fourteen criteria for evaluation obtained from the DEMATEL analysis are presented to gain insight into the interaction structure in the investment framework for the maritime energy economy in Vietnam. Total transmitted influence (D) is shown in Fig. 3(a) and indicates the influence that each criterion has on the other criteria in the system. The strongest transmitted influence (D = 6.444) shows that government incentives and financial support (C11) are the strongest drivers of maritime energy investments. This is followed by C10 (Port energy infrastructure readiness) (D = 6.056) and C12 (Compliance with IMO and national regulations) (D = 5.991), indicating that the preparation of port energy



(a) (b)

Fig. 2. IVq-ROF DEMATEL heatmaps: (a) normalized direct-relation matrix; (b) total-relation matrix

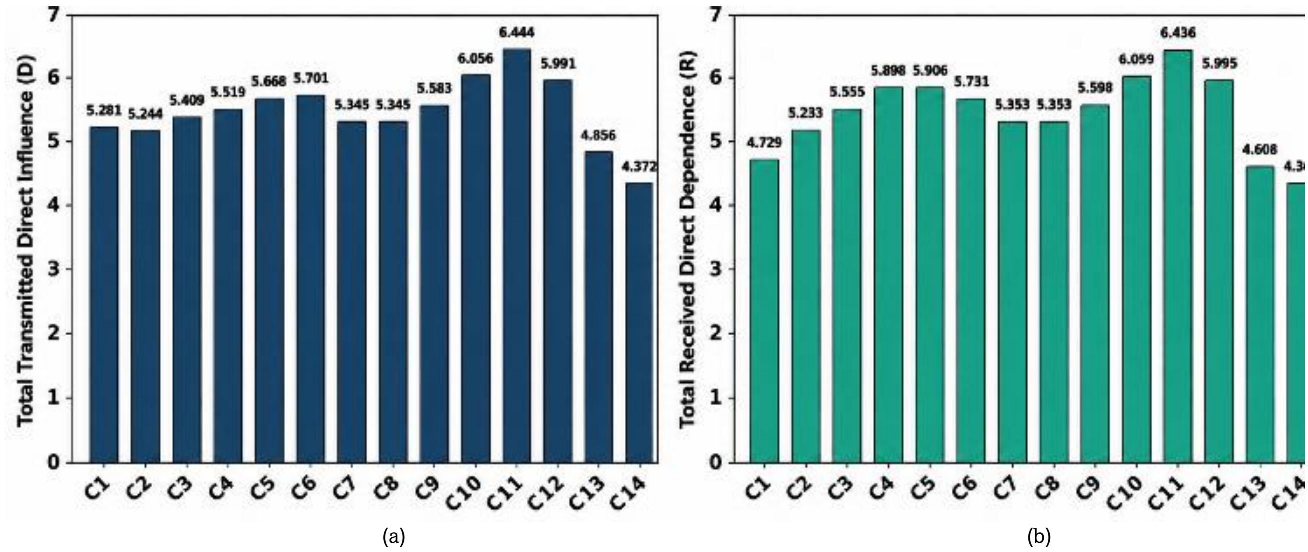


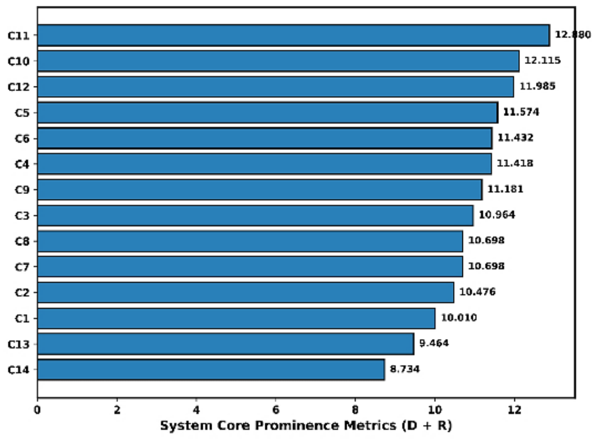
Fig. 3. Direct influence indices (a) Total transmitted influence (D) (b) Total received dependence (R)

infrastructure and compliance with IMO and national regulations are most important in influencing investment decisions. The criteria with moderate influence values include C6 (Maritime energy security), C5 (Availability of low-carbon marine fuels), C4 (Maritime energy efficiency improvement), C3 (Access to green maritime finance), C9 (Technology maturity), and C2 (Return on investment), indicating that these criteria make a significant contribution to the overall investment environment and interact with several other criteria. In contrast, C13 (Skilled workforce availability) (4.856) and C14 (Stakeholder acceptance) (4.372) fall on the low end of the influence transmitted, suggesting that they are more likely to act as enabling or supporting influences versus initiating influences in the decision network.

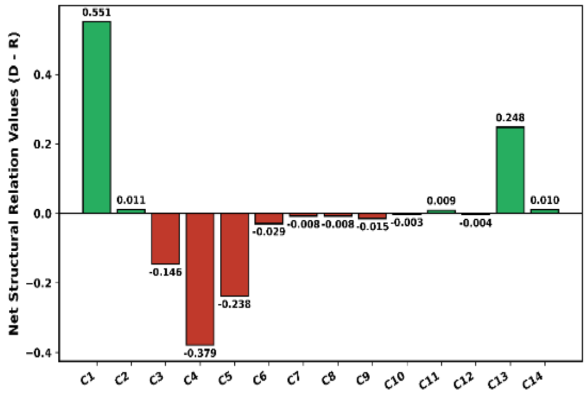
Fig. 3(b) shows the total received dependence (R), which is an indicator of the strength of the influence of the other criteria on each criterion. Just like the transmitted influence, C11 has the highest dependence value (R = 6.436), indicating that government incentives, as well, are not only important drivers but are strongly influenced by improvements in infrastructure, financing, technology, environmental targets, and regulations. C10 (6.059) and C12 (5.995) also show high dependence, reflecting the strong interconnection between infrastructure development, regulatory compliance, and the wider policy agendas. Some criteria are relatively high in their dependency, such as C4 (5.898), C5 (5.906) and C6 (5.731), which means that they depend on multiple dimensions of improvements in order to improve economic conditions, fuel availability and energy security. C1 (Port energy infrastructure investment cost) (4.729), C13 (4.608) and C14 (4.362) exhibit comparatively lower dependence; that is, these criteria are less likely to be influenced by other factors in the system. Generally, D and R values are close, indicating that policy support, infrastructure readiness and regulatory compliance play central roles in the close decision environment, highlighting the need for integrated, not uncoordinated, policy, technical, economic and environmental planning for successful maritime energy investments in Vietnam.

The prominence and causal characteristics of 14 investment criteria obtained from the DEMATEL analysis are shown in Fig. 4, which would help to explain the individual importance of each criterion in the overall decision system and the driving or dependent factors. Fig. 4(a) shows the absolute prominence power scaling profile (D + R), which represents the higher involvement of that criterion in the maritime energy economy system, and the value of D + R represents the level of interaction with other criteria. The highest prominence value (12.880) is obtained for C11 (Government incentives and financial support), indicating that policy incentives and financial assistance are the most central criteria to affect the successful implementation of maritime energy investments in Vietnam. This is followed by C10 (Port energy infrastructure readiness) (12.115) and C12 (Compliance with IMO and national regulations) (11.985), underlining that infrastructure availability and regulatory alignment are closely related and highly correlated with virtually all other investment criteria. The other categories include C5 (Availability of low-carbon marine fuels) (11.574), C6 (Maritime energy security) (11.432), C4 (Maritime energy efficiency improvement) (11.418), C9 (Technology maturity) (11.181) and C3 (Access to green maritime finance) (10.964), which are also significant in the assessment of effectiveness and sustainability of maritime energy investments. The environmental criteria, C7 (Greenhouse gas emission reduction) and C8 (Environmental sustainability), both have a prominence value equal to 10.698, indicating a balance between these two criteria and the others.

Relatively lower prominence values are achieved for C2 (Return on investment) (10.476), C1 (Port energy infrastructure investment cost) (10.010), C13 (Skilled workforce availability) (9.464) and C14 (Stakeholder acceptance) (8.734), indicating relatively lower systemic influence, but they are still of practical relevance. The net causal characterization (D − R) is shown in Figure 4(b), distinguishing driving (positive) and dependent (negative) criteria. Positive values are in the cause group; the criteria C1 (+0.551), C13 (+0.248), C2 (+0.011), C11 (+0.009), and C14 (+0.010) have positive values, which means that these criteria mainly influence other criteria, but not themselves. Especially, C1 stands out as the most powerful criterion for driving the investment decision, indicating that financing, infrastructure development, technology adoption, and regulation implementation are greatly influenced by the investment cost decision. Conversely, C4 (−0.379), C5 (−0.238), C3 (−0.146), C6 (−0.029), C9 (−0.015), C7 (−0.008), C8 (−0.008), C12 (−0.004), and C10 (−0.003) belong to the effect group, indicating that improvements in these criteria largely depend on changes in the driving factors. The relatively small magnitudes of some D − R values indicate a very strong interdependence and integrated Vietnamese maritime energy system, while the strong positive influence of investment cost and the availability of workforce indicates that investment cost and human resource



(a)



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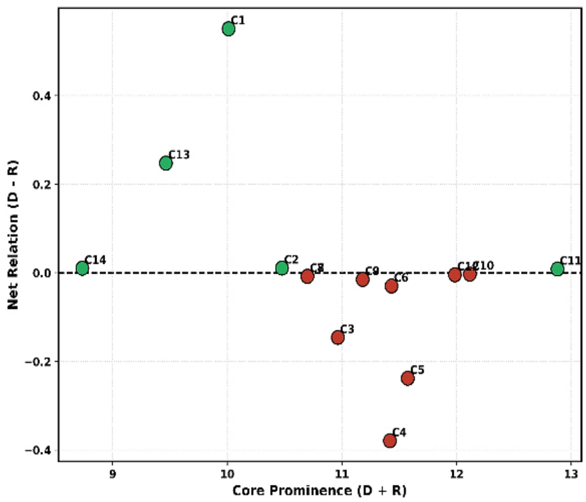

(c)

Fig. 4. DEMATEL causal analysis results. (a) Prominence values (D+R). (b) Net causal effects (D−R). (c) Cause–effect relationship diagram illustrating the distribution of criteria within the causal network

development are essential factors to be a catalyst for promoting Vietnam's maritime energy economy.

The cause–effect relationship diagram as derived from the DEMATEL analysis is shown in Fig. 4(c), with the horizontal axis indicating the prominence (D + R) and the vertical axis indicating the net relation (D − R). The prominence value indicates the overall importance of each criterion of the maritime energy economy system, while the net relation differentiates between the cause group (D − R > 0) and effect group (D − R < 0). Factors on the right side of the figure are more significant to the system because they are more interdependent with other factors, and factors above the horizontal axis mainly affect other factors, and those below the horizontal mainly are affected by the system. C11 (Government incentives and financial support) has the highest prominence with a slightly positive net relation and thus acts as an important driver and is highly connected with the overall decision construct. C10 (Port energy infrastructure readiness) and C12 (Compliance with IMO and national regulations) also have high prominence, but somewhat negative net relation values, indicating that they are also among the most important criteria, but that their performance is mostly dependent on improvements in other driver criteria. Based on the highest positive D − R value, C1 (Port energy infrastructure investment cost) is identified as the strongest causal criterion, which shows that investment cost has a significant impact on financing, infrastructure development, technology deployment, and policy implementation. C13 (Skilled workforce availability) and C14 (Stakeholder acceptance) are also part of the cause group, as they provide a supportive role in enabling maritime energy investments. On the other hand, the effect group consists of C3, C4, C5, C6, C8, C9, C10 and C12, meaning the improvement of these criteria is rather a result of the change of the causal criteria. More generally, government support, investment cost, workforce capability and stakeholder acceptance are the key drivers, and infrastructure, energy, technological and environmental are key outcomes of coherent policy and investment measures in Vietnam's maritime energy economy

3.2 Evaluation of Interaction-Aware Weight Allocations

Fig. 5 presents the symmetrical structural synergy co-dependency map, which illustrates the intensity of pairwise interactions among the fourteen evaluation criteria based on the total relation matrix obtained from the DEMATEL analysis. The color gradient represents the magnitude of mutual influence, where lighter shades indicate relatively weak interactions and darker shades correspond to stronger structural synergies between criteria. The diagonal elements are zero because self-influence is not considered. The heatmap reveals that C10 (Port energy infrastructure readiness), C11 (Government incentives and financial support), and C12 (Compliance with IMO and national regulations) exhibit the strongest co-dependency with most other criteria, with interaction values generally ranging from 0.90 to 1.00. In particular, the strongest relationship is

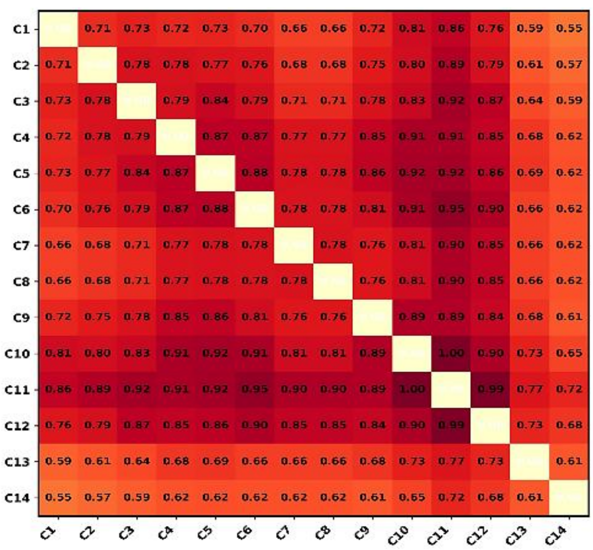

Fig. 5. Symmetrical structural synergy co-dependency map

observed between C10 and C11 (1.00), demonstrating that infrastructure readiness and government support are mutually reinforcing and jointly determine the effectiveness of maritime energy investments. Similarly, strong interactions are evident among C10, C11, C12, C5, and C6, indicating that infrastructure development, policy support, regulatory compliance, low-carbon fuel availability, and maritime energy security constitute the core structural network of the system. Conversely, C13 (Skilled workforce availability) and C14 (Stakeholder acceptance) display comparatively lower interaction values with most criteria, generally between 0.55 and 0.73, suggesting that although they contribute to system performance, their structural connectivity is relatively weaker. Overall, the heatmap demonstrates a highly interconnected investment framework in which policy, infrastructure, regulatory, and energy-related criteria collectively form the dominant synergistic foundation for advancing Vietnam's maritime energy economy.

The standalone DEMATEL weights with the interaction-adjusted Choquet weights, thereby illustrating how consideration of interdependencies among criteria modifies their relative importance within the maritime energy economy framework (Fig. 6(a)). The grey bars represent the original DEMATEL weights, whereas the blue bars correspond to the weights recalculated using the Choquet integral, which explicitly accounts for interactions among criteria. The comparison shows that several criteria experience noticeable weight increases after incorporating interaction effects. C11 (Government incentives and financial support) records the largest weight in both approaches, increasing from 0.084 to 0.095, confirming that policy support becomes even more influential when its strong interactions with infrastructure, finance, technology, and regulatory criteria are considered. Likewise, C10 (Port energy infrastructure readiness) increases from 0.079 to 0.085, while C5 (Availability of low-carbon marine fuels) rises from 0.075 to 0.078, reflecting the additional importance gained through their close relationships with other strategic factors. Moderate increases are also observed for C4, C6, C3, and C9, indicating that these criteria benefit from positive interaction effects within the overall system. Meanwhile, C1 (Port energy infrastructure investment cost) declines from 0.065 to 0.060, C13 (Skilled workforce availability) decreases from 0.062 to 0.054, C14 (Stakeholder acceptance) declines from 0.057 to 0.046, and C2 experiences a slight reduction, suggesting that these criteria contribute more independently and receive less additional importance from system interactions. Overall, the figure demonstrates that incorporating interaction effects redistributes criterion importance, emphasizing policy, infrastructure, and energy-related factors while slightly reducing the relative contribution of more isolated criteria, thereby providing a more comprehensive representation of investment priorities in Vietnam's maritime energy economy.

Fig. 6(b) illustrates the Choquet net parameter space shares, presenting the percentage contribution of each evaluation criterion after incorporating interaction effects through the Choquet integral. Unlike conventional weighting methods that assume criterion independence, the Choquet integral accounts for interdependencies among criteria, thereby providing a more realistic representation of their collective importance in Vietnam's maritime energy economy. The pie chart reveals that C11 (Government incentives and financial support) contributes the largest proportion (9.5%) to the overall decision framework, confirming that supportive policies, financial incentives, and investment assistance constitute the principal driving force for sustainable maritime energy development. The second and third highest shares are associated with C10 (Port energy infrastructure readiness) (8.5%) and C12 (Compliance with IMO and national regulations) (8.4%), highlighting the importance of adequate infrastructure and regulatory compliance in facilitating energy transition within the maritime sector. Moderate contributions are observed for C5 (Availability of low-carbon marine fuels) (7.8%), C6 (Maritime energy security) and C4 (Maritime energy efficiency improvement) (both 7.6%), followed by C9 (Technology maturity) (7.3%) and C3 (Access to green maritime finance) (7.1%). Environmental criteria, namely C7 (Greenhouse gas emission reduction) and C8 (Environmental sustainability), each contribute 6.8%, indicating their balanced role within the integrated decision system. Comparatively smaller shares are recorded for C2 (Return on investment) (6.5%), C1 (Port energy infrastructure investment cost) (6.0%), C13 (Skilled workforce availability) (5.4%), and C14

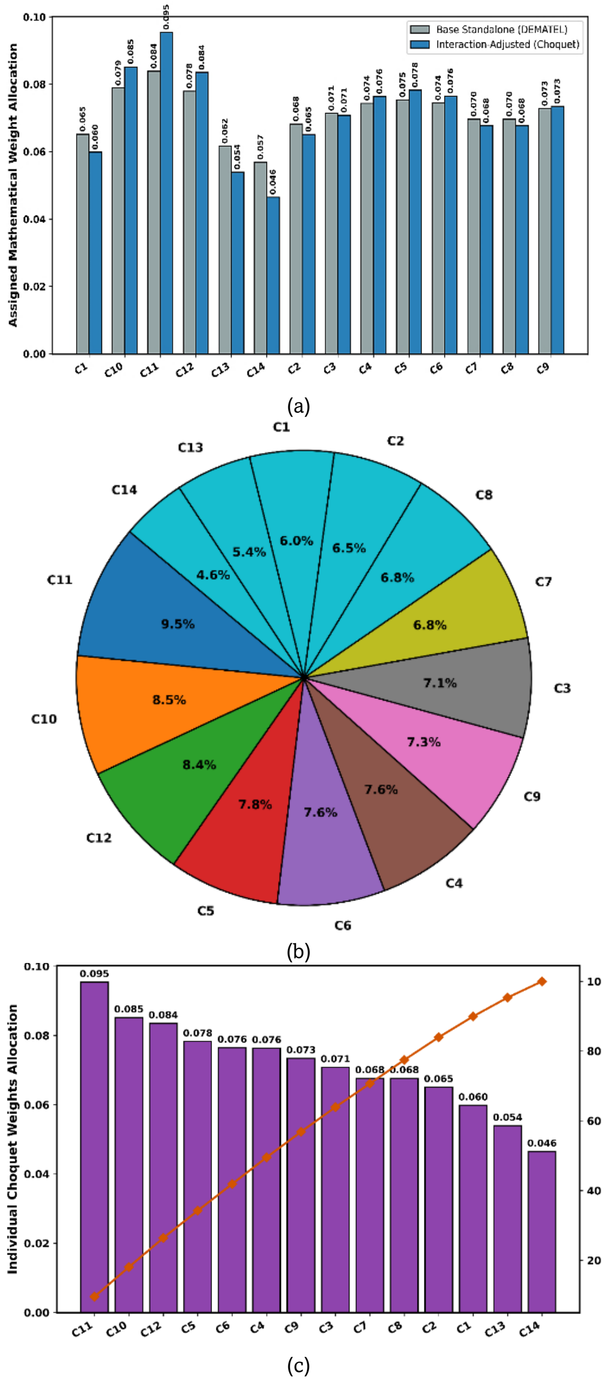

Fig. 6. Interaction-adjusted Choquet weights: (a) DEMATEL vs. Choquet weights; (b) criterion contributions; (c) Pareto ranking

(Stakeholder acceptance) (4.6%). Overall, the distribution demonstrates that policy, infrastructure, regulatory, and energy-related considerations collectively dominate the decision-making process, while economic and social factors play complementary yet essential supporting roles.

Fig. 6(c) presents the weight aggregation Pareto priority profile, ranking the evaluation criteria according to their final Choquet-integrated weights and illustrating their cumulative percentage contribution to the overall decision process. The purple bars represent the normalized Choquet weights, while the orange line depicts the cumulative contribution of the ranked criteria, thereby identifying the most influential parameters within Vietnam's maritime energy economy. The ranking indicates that C11 (Government incentives and financial support) receives the highest final weight (0.095), reaffirming its dominant role in stimulating investment, reducing financial barriers, and supporting the adoption of clean maritime energy technologies. This is followed by C10 (Port energy infrastructure readiness) (0.085) and C12 (Compliance with IMO and national regulations) (0.084), emphasizing that infrastructure preparedness and regulatory alignment are fundamental prerequisites for successful implementation of maritime energy projects. The subsequent positions are occupied by C5 (Availability of low-carbon marine fuels) (0.078), C6 (Maritime energy security) and C4 (Maritime energy efficiency improvement) (both 0.076), C9 (Technology maturity) (0.073), C3 (Access to green maritime finance) (0.071), and C7 and C8 (both 0.068), demonstrating their substantial contributions to the overall evaluation framework. Lower-ranked criteria include C2 (Return on investment) (0.065), C1 (Port energy infrastructure investment cost) (0.060), C13 (Skilled workforce availability) (0.054), and C14 (Stakeholder acceptance) (0.046). The steadily increasing cumulative contribution curve indicates that the first several criteria account for a significant proportion of the total decision weight, reflecting a Pareto-like distribution in which policy support, infrastructure readiness, regulatory compliance, and energy-related factors collectively dominate the evaluation. These findings suggest that prioritizing improvements in these high-ranking criteria would generate the greatest overall impact on advancing Vietnam's maritime energy economy while ensuring effective allocation of financial and institutional resources.

3.3 Strategic Prioritization of Maritime Investments

Fig. 7 presents the final prioritized weight ranks mapped by component importance, illustrating the ultimate ranking of the fourteen evaluation criteria based on their interaction-aware Choquet weights after incorporating the causal

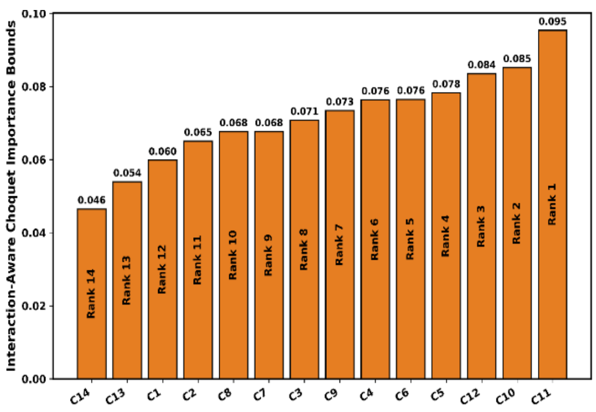

Fig. 7. Final prioritized weight ranks mapped by component importance

interdependencies identified through the DEMATEL analysis. The ascending arrangement of the bars enables a clear comparison of the relative contribution of each criterion to Vietnam's maritime energy economy while simultaneously displaying their final ranking positions. The figure indicates that C11 (Government incentives and financial support) achieves the highest importance weight (0.095) and is therefore ranked first, demonstrating that policy incentives, subsidies, fiscal support, and green financing mechanisms constitute the most influential factors for accelerating maritime energy transition in Vietnam. C10 (Port energy infrastructure readiness) ranks second with a weight of 0.085, highlighting the necessity of developing adequate bunkering facilities, shore power systems, storage infrastructure, and grid connectivity to facilitate the adoption of alternative marine fuels. C12 (Compliance with IMO and national regulations) occupies the third position (0.084), emphasizing the critical role of regulatory alignment with international decarbonization targets and national maritime policies. The subsequent rankings include C5 (Availability of low-carbon marine fuels) (0.078), C6 (Maritime energy security) and C4 (Maritime energy efficiency improvement) (both 0.076), C9 (Technology maturity) (0.073), C3 (Access to green maritime finance) (0.071), and C7 (Greenhouse gas emission reduction) together with C8 (Environmental sustainability) (both 0.068), reflecting their significant contributions to achieving a resilient and sustainable maritime energy system. In contrast, C2 (Return on investment) (0.065) and C1 (Port energy infrastructure investment cost) (0.060) receive comparatively lower rankings, indicating that although economic feasibility remains important, its overall contribution is moderated when interactions with policy, infrastructure, and technical factors are considered. The two lowest-ranked criteria are C13 (Skilled workforce availability) (0.054) and C14 (Stakeholder acceptance) (0.046), suggesting that these factors function primarily as enabling conditions rather than dominant strategic drivers within the overall investment framework. Overall, the final prioritized ranking demonstrates that policy support, infrastructure readiness, and regulatory compliance collectively form the principal pillars for strengthening Vietnam's maritime energy economy, while technological, environmental, economic, and social factors provide complementary support for achieving a successful and sustainable energy transition.

4. Policy recommendations

Based on the results of the IVq-ROF DEMATEL–Choquet Integral analysis, several strategic recommendations can be proposed to boost the development of Vietnam's maritime energy economy. In all results, the criterion with the greatest influence is government incentives and financial support (C11), which reinforces the need for public policy to continue as the main factor for the maritime energy transition. Policymakers should thus work towards bolstering financial support via targeted subsidies, tax measures, preferential lending, green bonds, and public-private partnership (PPP) models to lower the investment risks of low-carbon maritime energy projects. A clear and consistent policy framework would also boost investor confidence, thereby encouraging more private sector involvement. Additionally, the analysis shows that the second and third most important criteria, respectively, are port energy infrastructure readiness (C10) and compliance with IMO and national regulations (C12). Therefore, Vietnam should focus on the modernization of ports infrastructure such as shore power facilities, alternative fuel bunkering systems, hydrogen and ammonia storage terminals, smart energy management systems, renewable energy integration in ports. At the same time, by continuously harmonizing national maritime regulations with the IMO decarbonization strategy and new international environmental standards, the regulatory certainty will be guaranteed and international trade competitiveness will be supported.

The high scores for availability of low-carbon marine fuels (C5) and maritime energy security (C6) show that the diversification of marine fuel supplies will be needed in the future. Investment is therefore needed in national pathways to grow domestic production and supply chains for green hydrogen, green methanol, green ammonia, sustainable biofuels and renewable electricity as a way to decrease reliance on fossil fuels imports and to boost energy resilience. This diversification will help also to increase the access of fuel for shipping operators and will contribute to their long-term decarbonization goals. Results also show that the three factors of maritime energy efficiency improvement (C4), technology maturity (C9), and green maritime finance (C3) have an important supporting function in the investment system. Investments in digital technologies, artificial intelligence (AI) based energy management systems (EMS), smart port operations, predictive maintenance and energy efficient vessel technologies should be encouraged, accordingly. At the same time, financial institutions should scale up green financing facilities, sustainability linked financing, and climate investment funds to fund technology solutions and innovation across the maritime value chain.

While emission reduction (C7) and environmental sustainability (C8) were assigned moderate priority weights, the two are still crucial outcomes of an integrated maritime energy strategy. Environmental performance indicators should therefore be integrated into national port development plans, shipping modernization programs and investment evaluation frameworks, to ensure that economic development goes hand in hand with emissions reduction and ecosystem protection. Further strengthening of sustainable decision-making can be achieved by continuous environmental monitoring and lifecycle-based performance assessment. The results of return on investment (C2) and port energy infrastructure investment cost (C1) indicate that the financing issue should not be assessed alone, but in the overall policy and infrastructure environment. A well-designed government incentive and regulatory support can significantly enhance the viability of the project, reduce risks and shorten payback periods, and increase the competitiveness of capital-intensive maritime energy projects for domestic and international investors. Lastly, while stakeholder acceptance (C14) and skilled workforce availability (C13) secured relatively lower importance weights, they are enabling conditions for successful implementation. It is necessary to promote specialized training and education on maritime energy technology, hydrogen systems, renewable fuels, digital port operations and environmental management in Vietnam. There is also a need to foster active involvement of government bodies, port authorities, shipping companies, energy suppliers, financial institutions, research institutions, and local communities in raising awareness, promoting knowledge sharing, and gaining public acceptance of maritime energy transition projects.

To facilitate practical implementation, the identified priorities can be translated into phased policy actions for Vietnam. In the short term (1–3 years), policymakers should prioritize the introduction of targeted financial incentives, green financing mechanisms, tax concessions, and regulatory guidelines that encourage investment in low-carbon maritime technologies. Medium term (3-7 years) investment priorities should be in upgrading strategic ports through the installation of shore power facilities, alternative fuel bunkering infrastructure, hydrogen and ammonia storage facilities, and digital energy management platforms, as well as enhancing the skills of the maritime energy workforce through dedicated maritime energy training programs. In the long-term (2030+), national policies should focus on large-scale deployment of renewable marine fuel supply chains, integration of smart and low-carbon port ecosystem, continuous adaptation to IMO decarbonisation regulations, and on the expansion of public-private partnerships to mobilise long-term capital for maritime energy infrastructure. This approach allows for a gradual rollout, giving policymakers a realistic plan to drive Vietnam's maritime energy transition more quickly, ensuring economic competitiveness, energy security, and environmental sustainability.

5. Conclusion

In this study, an integrated framework for prioritizing the key investment drivers for the maritime energy economy in Vietnam based on the Interval Valued q-Rung Orthopair Fuzzy DEMATEL–Choquet Integral framework was proposed. The proposed framework successfully identified the complex interactions between fourteen evaluation criteria of economic, energy, environmental, technical, regulatory and social aspects by integrating the causal relationship analysis of DEMATEL and the interaction-aware weighting ability of the Choquet integral. In addition to the Vietnam's maritime energy economy, the main methodological contribution of this study is the development of an interaction-aware decision-support framework combining IVq-ROF DEMATEL and Choquet Integral to simultaneously deal with uncertainty, causal relationships, and criterion interactions. The proposed framework explicitly differentiates between causal influence, systemic prominence and interaction adjusted priorities which are not considered by existing MCDM methods that take criterion independence as their basic premise and thus offers more meaningful insights to complex investment decision problems. The methodology proposed is flexible enough to be applied to other energy planning or energy infrastructure investment areas where uncertainty, interdependent evaluation criteria and limited quantitative data are present. The findings show that policy support, infrastructure development, and regulatory alignment are the main three drivers for speeding up maritime energy transition in Vietnam, with the interaction-adjusted weight for government incentives and financial support being the highest (0.095), followed by port energy infrastructure readiness (0.085) and IMO and national regulations (0.084). Other key factors are the availability of low-carbon marine fuels (0.078), maritime energy security (0.076), maritime energy efficiency improvement (0.076) and technology maturity (0.073), underscoring the need for fuel supply security, operational efficiency, and technological development. The causal analysis also identified that the port energy infrastructure investment cost criterion had the highest $D - R$ value, indicating that it was the strongest driving criterion, whilst the highest $D + R$ value was government incentives and financial support indicating that it was the most prominent criterion within the investment network. Stakeholder acceptance (0.046) and skilled workforce availability (0.054) on the other hand got comparatively lower final weights which shows that these are more supporting rather than dominant strategic factors. All the results indicate that an integrated policy strategy is needed to support financial incentives, build port energy facilities, comply with regulations, implement low-carbon fuel use, and boost technological innovation to realize the success of Vietnam's maritime energy economy development. Future research could build on the framework by adding more investment options, dynamic MCDM approaches, or comparative studies between countries, among other potential extensions, to facilitate regional maritime energy planning and sustainable development of the blue economy.

The proposed framework is based on expert judgments and therefore reflects subjective assessments despite the use of IVq-ROF sets to model uncertainty. Also, the framework represents a static decision environment specific to Vietnam's maritime energy sector and does not explicitly account for temporal changes in policy, technology, or market conditions. These limitations are acknowledged to provide a balanced interpretation of the study.

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