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Review

A Conceptual Transdisciplinary Framework to Overcome Energy Efficiency Barriers in Ship Operation Cycles to Meet IMO's Initial Green House Gas Strategy Goals: Case Study for an Iranian Shipping Company

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Abstract: Through a systematic, holistic and transdisciplinary approach and by proposing five phases of "goal information", "system analyzing", "scenario construction", "multi-criteria assessment" and "strategy building", the study offers a process for recognizing and prioritizing energy-efficient barriers in the ship's operational cycle according to decision-makers' concerns. The study utilized the proposed conceptual transdisciplinary framework for overcoming energy efficiency barriers in ship operating cycles. The framework categorizes the barriers in the operational cycle into five disciplines, i.e., operations, policy and regulations, technology and innovation, human element and economics, and applies the framework to an Iranian shipping company. The results show that the economic discipline has the highest priority, and the human discipline has the least importance for the company's decision makers. In addition, "adverse selection" (operational discipline), "policy implementation" (policy and regulatory discipline), "split incentives" (economic discipline), "limited access to capital" (economic discipline) and "imperfect budgeting" were the main barriers to energy efficiency in the company.

Keywords: air emissions; energy efficiency barriers; energy policy; life cycle management; energy management system; transdisciplinary

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1. Introduction

Maritime transport is the most fuel and cost-efficient form of transport, accounting for 80% of freight volume, and plays an important role in global trade [1]. Air emissions are one of the main negative externalities of maritime transport. Shipping accounts for 2.89% of global greenhouse gas emissions and has increased by 9.6% and international shipping by 5.6% since 2013 [2]. The International Maritime Organization (IMO), the regulatory body for international shipping, adopted its first strategy to reduce greenhouse gas emissions from ships in 2018, with the aim of phasing out greenhouse gas emissions from international shipping in the 21st century. The ambition of this strategy is to reduce carbon intensity from ships by 40% by 2030 and by 70% by 2050 compared to 2008, and total annual greenhouse gas emissions from international shipping by 50% by 2050, and to reach zero by the end of the century [3].

By introducing an Energy Efficiency Design Index (EEDI) for new ships, a Ship Energy Efficiency Management Plan (SEEMP) for all ships over 400 gross tons and a Fuel Consumption Data Collection System (DCS) for all ships over 5000 gross tons, the IMO has sought to address greenhouse gas emissions from maritime transport [4]. In addition, MEPC 75 agreed on a combined technical measure (Energy Efficiency Existing Ship Index, EEXI) and an operational measure (Carbon Intensity Indicator, CII) to accelerate the shipping industry's reduction in CO_2 emissions from existing ships [3]. A target-based approach has been introduced to use alternative methods to meet the requirements for improving the energy efficiency of ships. This allows ship owners to choose the most cost-effective options based on their priorities for improving energy efficiency on board the ship, depending on many factors such as the size and type of the ship, its age and trading area [5]; however, studies show that the use of various clean alternative fuels and the improvement of energy on board ships are important factors in achieving the IMO targets [6–10].

Energy efficiency is a crucial factor and plays a key role in achieving the IMO targets, and as fuel costs account for 60% of ships' operating costs [11], ship owners are keen to improve energy efficiency on board their fleets. In addition, rising energy costs and regulations are driving ship owners' interest in improving the energy efficiency of their fleet; however, in real cases, there is a gap between potential energy efficiency and actual energy efficiency measures on board ships, and this is due to a number of barriers that prevent implementation [12]. Ship owners and managers want to identify the barriers to energy efficiency on board their fleet and overcome the energy efficiency gap, as it leads to economic benefits for them and helps them to comply with IMO greenhouse gas regulations.

Vakili et al. [13] designed and developed a transdisciplinary framework for identifying barriers in the construction phase of the ship life cycle and successfully applied it in an Iranian shipyard. The authors of the research proposed further studies to recognize the barriers to improving energy efficiency in other phases of the ship life cycle to overcome the barriers to energy efficiency in the maritime industry within the life cycle perspective [13]. This will help industry decision makers, policy makers and regulators to have a holistic view on how to overcome the barriers to energy efficiency in the industry, and the approach is expected to accelerate the carbon reduction in the industry.

In light of the above, the study has taken into account the principles of the framework proposed by Vakili et al. [13], which has a holistic, systematic and interdisciplinary character. The framework was applied to an Iranian shipping company and identified the interrelationships and interactions between different types of barriers during the operational phase of the vessels, both on board the vessels and in the offices. Interviews were conducted with five different experts and managers from the company. In order to obtain a holistic view of identifying the barriers to energy efficiency, the authors aimed to select key people who have an important role in improving energy efficiency both on board the vessels and in the offices. To achieve this goal, a captain and a chief engineer of the fleet were selected for interviews, as they are the key people responsible for the energy efficiency measures on board the vessels, as well as the head of fleet operations, the head of fleet engineering and the company's managing director, who have a crucial role in improving energy efficiency in the fleet. The application of the framework to ship owners accelerates the reduction in carbon emissions from their fleets and gives ship managers a clear picture of the barriers within their fleets and organizations, helping managers and policy makers to adopt appropriate energy strategies and policies to overcome them, leading to additional economic benefits and accelerating the transition to zero emissions and the achievement of the IMO's GHG strategy targets [12].

The novelty of the study is to propose a holistic, systematic and transdisciplinary framework to overcome barriers to energy efficiency in shipping companies. In addition, the study applied the proposed framework to a large shipping company with vessels of different sizes and types with different portfolios, including inland waterway transport, local transport, international transport and offshore operations. By considering the main key stakeholders, i.e., the master and the chief engineer (providing the end-user's perspective on board the vessels), the head of fleet operations and the head of fleet engineering (providing the operators' perspective) and the company's CEO (providing the ship-owners' perspective), the study aimed to consider and cover the main stakeholders' perspectives in improving energy efficiency in a similar holistic platform. By implementing the framework and the results of the study, it is expected that the company will be able to identify barriers to energy efficiency and overcome them to accelerate the reduction in carbon emissions from the fleet and help the company meet the IMO's initial greenhouse gas strategy targets.

Section 2 provides a literature review and discusses different barriers to energy efficiency in the classical categorization and ship operation cycle. The methodology and methods are explained in Section 3. Section 4 presents the results of the case studies and the related discussion. Finally, the conclusion is drawn in Section 5.

2. Literature Review

Energy efficiency is a key issue in reducing carbon emissions; however, there may be an inherent discrepancy between the best implementation and real-time implementation, which is called the "energy efficiency gap" [14,15]. This is due to mechanisms that prevent investment in energy-efficient and economically effective technologies [12,16–18], which is called the "energy efficiency barrier".

Barriers to energy efficiency have been extensively studied in different aspects and groups. Blumstein et al. [19] have classified barriers to energy efficiency into six categories: improper incentives, scarcity of information, regulation, market structure, financing and adaptation, and Hirst and Brown [20] have classified energy efficiency hinders into two categories: structural barriers and behavioral barriers. Howarth and Andersson [21] considered lack of information, problems with commissioners and agents, consumer uncertainty and lack of access to credit as barriers in the energy-using equipment market, and Eyre [22] classified barriers as information barriers, problems in separating costs and benefits, barriers to accessing capital, tariff barriers, externalities and limited rationality. IPCC (Intergovernmental Panel on Climate Change) [23] classified barriers to energy efficiency as technological innovation, prices, finance, trade and environment, market structure, institutional framework, information provision and social, cultural and behavioral norms and standards, and Fleiter et al. [24] classified barriers to energy efficiency as twelve different characteristics. In addition, empirical studies such as Thollander and Ottson [14], Cagno and Trianni [25], Dixon et al. [26], Nehler et al. [27], Lane et al. [28] and Vakili et al. [13] have identified and classified barriers to energy efficiency in various industries and in different categories.

Considering the above, market failures are the main cause of energy efficiency deficiencies and consist of four characteristics: imperfect market, imperfect competition, imperfect information and asymmetric information [29], and act as the main barriers to improving energy efficiency [30,31]; however, the barriers to energy efficiency contain broader aspects and include economic, organizational and behavioral barriers [32]. Table 1 shows the categories of energy efficiency. Based on the literature review, the barriers to energy efficiency are categorized into four parts, namely economic market failure, economic non-market failure [32,33], behavioral barriers and organizational barriers [33,34].

2.1. Economic Market Failure

The economic market failure is classified into "imperfect information", "adverse selection", "principal-agent relationship" and "split incentives". The "incomplete information" is due to lack of information leading to increased energy efficiency gaps and "adverse selection" is due to lack of information about the energy performance of the service and technology [35]. In addition, a "principle-agent relationship" arises when the principle applies strict monitoring and control of the agent. Finally, "shared incentives" arise when investors cannot benefit from energy efficiency investments [30,32,34].

2.2. Economic Failure That Is Not a Market Failure

Non-market economic failures are classified into "hidden costs", "access to capital", "risk" and "heterogeneity". The "hidden costs" are costs that are not taken into account in the investment. They are due to overhead costs, production disruptions and interruptions, costs of data and information collection and related analysis, etc. "Lack of access to capital" is usually one of the main barriers to improving energy efficiency [13] and consequently, the "risk" of investment can increase the energy efficiency gap. Finally, "heterogeneity" is due to the fact that technology may not be energy and cost-efficient in all sectors and under all conditions [30,32,34].

Table 1. Classification of barriers to energy efficiency according to [30,32–34].

Category	Theoretical Barriers	Comments
Economic market failure	Imperfect information	Imperfect and lack of information may lead to enhance of energy efficiency gap as the cost-effective energy efficiency measures might be missed.
	Adverse selection	Suppose the vendor has more information about the energy performance of the service and/or the technology than the buyer. In that case, the buyer may select the service and/or the technology based on the visible aspects such as initial price, shape, design and color.
	Principle agent relationship	Since the principle cannot see what the agent is doing, it may lead to strict monitoring and controlling of the agent by the principal, this type of behavior can act as an energy efficiency barrier.
	Split incentive	If a person or department cannot benefit from the energy efficiency investment, it can lead to less enthusiasm in applying energy efficiency measures and an increase in the energy efficiency gap.
Economic non-market failure	Hidden cost	Overhead costs, production disruption and interruption, cost of data and information collection and related analysis, etc., are some examples of hidden costs, which may lead to hinder deploying energy efficiency measures.
	Access to capital	Lack of access to capital can lead to an increase in the energy efficiency gap.
	Risk	Risk in investment can lead to an increased energy efficiency gap. Considering the short payback period can reduce the risk of the investment in the sector accordingly.
	Heterogeneity	The technology or measure might not be cost-efficient suitable in all locations, industries, etc.
Behavioral barriers	Form of information	Information has an important role in overcoming energy efficiency barriers. The information must be Specific, Vivid, Simple and Personal (SVSP).
	Credibility and trust	The credibility and trustworthiness of the information provided are essential. Lack of trust in information providers may lead to inappropriate choice of energy-efficient service and/or technology.
	Values	If the individuals, especially the ones in the top management, have real ambitions to increase energy efficiency, the efficiency improvement is most likely to be successful.
	Inertia	The opponent of individuals to change may lead to overlooking cost-effective energy efficiency measures.
	Bounded rationality	Instead of being made decisions within the perfect information, decisions are made in a constrained environment that results in inbounded and non-rational decisions.
Organizational	Power	The low status of the energy managers in the organization may cause energy issues to take low priority and this leads to an increase in energy efficiency.
	Culture	Organizations by developing a culture characterized by environmental values can promote energy efficiency.

2.3. Behavioral Barriers

Behavioral barriers fall into five categories: "information form", "credibility and trust", "values", "inertia" and "limited rationality". "Information" plays a crucial role in reducing energy efficiency gaps. The information must be specific, vivid, simple and personal (SVSP) and the credibility and trustworthiness of information play a crucial role in minimizing energy efficiency gaps [30,36,37]. In addition, "lack of trust" in the information provider can lead to the selection of an inappropriate energy-efficient service and/or technology. The values of individuals and organizations are also an important factor in improving energy efficiency; however, individuals are usually not in a position to change their behavior in a way that could affect their and thus the organization's value. Finally, "constrained radiation" occurs when energy efficiency decisions are made in a constrained environment, resulting in unconstrained and non-rational decisions [32–34].

2.4. Organizational Barriers

The organizational barriers are categorized into "power" and "culture". Lack of "power" and status of an energy manager in the organization can lead to increased differences in energy efficiency. In addition, the "culture" of the individual and the organization is an important factor in encouraging managers to invest in energy efficiency measures. A lack of environmental culture within organizations can increase barriers to energy efficiency and hinder energy efficiency improvements [32–34].

2.5. Barriers to Energy Efficiency in Shipping

Energy efficiency is an important policy to address climate change and related challenges, and it can also promote a sustainable future [38–40]. According to the IPCC (2017) report, energy efficiency is one of the most important tools to address climate change. In order to improve energy efficiency in the maritime cluster, a policy in the marine energy sector is crucial, and it is invoked to justify the policy in the maritime energy sector. To reduce the carbon footprint of the maritime sector, a holistic systemic policy and a broader vision (life-cycle perspective) must be taken into account [13].

There is great potential in the maritime industry to improve energy efficiency. Johansson and Anderson [41], through interviews and applications from other industries, classified the barriers as informational, transactional and organizational barriers and discussed related information asymmetries and power structures within the organization, and encouraged shipping company managers to review their organizations to identify the key barriers. Acciaro et al. [42] present barriers to the implementation of cost-saving technologies in shipping companies. The barriers are classified based on the results of a survey of Norwegian shipping companies as safety and reliability, technical uncertainty, behavior, market constraints, and economic constraints and complexity. Rehmatulla and Smith [43] used a triangular research approach by examining surveys from shipping companies, ship contracts and analyzing data on energy efficiency. They concluded that the gap in energy efficiency is minimized if ship owners can recover the investment in energy efficiency through higher charter prices. In addition, they argued that the existence of market failures and barriers creates complexity for policy makers and that it would not be cost-effective to apply market-based measures in such an environment; however, according to various literature, pricing and the application of the ETS will lead to both a reduction in energy consumption [44,45] and a shift to cleaner energy sources [46].

Jafarzadeh and Utne [47] have introduced a framework to help ship owners and (energy) managers identify barriers. In the mentioned study, the barriers were classified as information barriers, economic barriers, barriers within and between organizations, technical barriers, political barriers and geographical barriers in the ship operation cycle. In addition, Dewan et al. [48] categorized the constraints for measuring energy efficiency performance within the shipping company as: shortage of information, financial barriers, organizational constraints, technical and technical limitations, political and geographical constraints. The study concluded that the identified barriers can be overcome through training of personnel both onboard and in the office. At the same time, some studies have focused on technical perspectives to improve energy efficiency on board ships, e.g., Rehmatulla and Smith [43], who analyzed thirty technical measures for energy efficiency and carbon reduction in shipping and evaluated them through a cross-sectional survey of shipping companies and operators.

In light of the above, the study has shown that there is a lack of a holistic, systematic and transdisciplinary research and the necessary tools to identify barriers to energy efficiency, improve energy efficiency, and accelerate decarbonization in a shipping company, taking into account the perspectives of the various key stakeholders.

3. Methodology

In the maritime industry, there is a shortage of scholars on a systematic and transdisciplinary research to identify barriers to energy efficiency and to analyze their interrelationship and feedback [13]. In areas where there is a lack of information, a conceptual framework supported by mathematical methods may be more effective than robust and rigorous models [49,50].

Table 2 shows the research design and sequences of the study. In this study, 5 steps were considered to develop the research.

Table 2. Sequence of study.

Steps	Actions
Step 1	- Conducting a systematic literature review; - Considering peer-reviewed articles, conference papers, industry and company guidelines in various sectors; - Identifying energy efficiency barriers in various sections.
Step 2	- Analyzing different energy barriers from the list; - Identifying the barriers related to energy efficiency improvement in the ship operation cycle.
Step 3	- Conducting an extensive literature review and categorizing the most important disciplines for solving the energy efficiency problems in the ship operation cycle; - Classified the disciplines into five categories of: operations, policy and regulation, technology and innovation, human element and economics; - Nominating the energy efficiency barriers (from the list in phase two) into five disciplines.
Step 4	- Utilizing two multi-criteria decision making (MCDM) methods, i.e., fuzzy analytical hierarchy process (FAHP) and fuzzy technique for order of preference by similarity to ideal solution (FTOPSIS) to identify and rank the energy efficiency barriers; - Identifying the interactions among the barriers.
Step 5	- Implementing the framework in a case study (an Iranian shipping company) and identifying the energy efficiency barriers of the company; - Utilizing the MCDM methods for ranking and identifying the relation and interaction among the identified barriers.

In addition, as Table 3 shows in order to overcome the energy efficiency barriers within the five disciplines, four criteria have been considered.

Table 3. Determined criteria to overcome energy efficiency barriers.

Criteria	Definition
Criterion 1	Considering the severity of the energy efficiency barriers in hindering the improvement of energy efficiency in the company.
Criterion 2	The ease of removing the energy efficiency barriers with respect to the company's characteristics.
Criterion 3	The impact of removing the energy efficiency barriers in improving energy efficiency in the company.
Criterion 4	The impact of removing the energy efficiency barriers in the economic performance of the company.

3.1. Systematic Literature Review

A systematic literature review was used as part of step 1 of this research (see Figure 1). To choose the databases, the authors made a list of all subjects, fields and disciplines that can provide information on the topic. In this order, the authors looked at previous research and existing literature on the topic, to find out what has already been performed and what databases have been used. The next step was to select the final databases related to the topic, subjects, fields and disciplines for this study. Many references were listed, but considering the time period and the quality of the provided papers in the databases, the authors chose the best and top databases in the field, namely Scopus, Science Direct, Google Scholar, Research Gate and EBSCO.

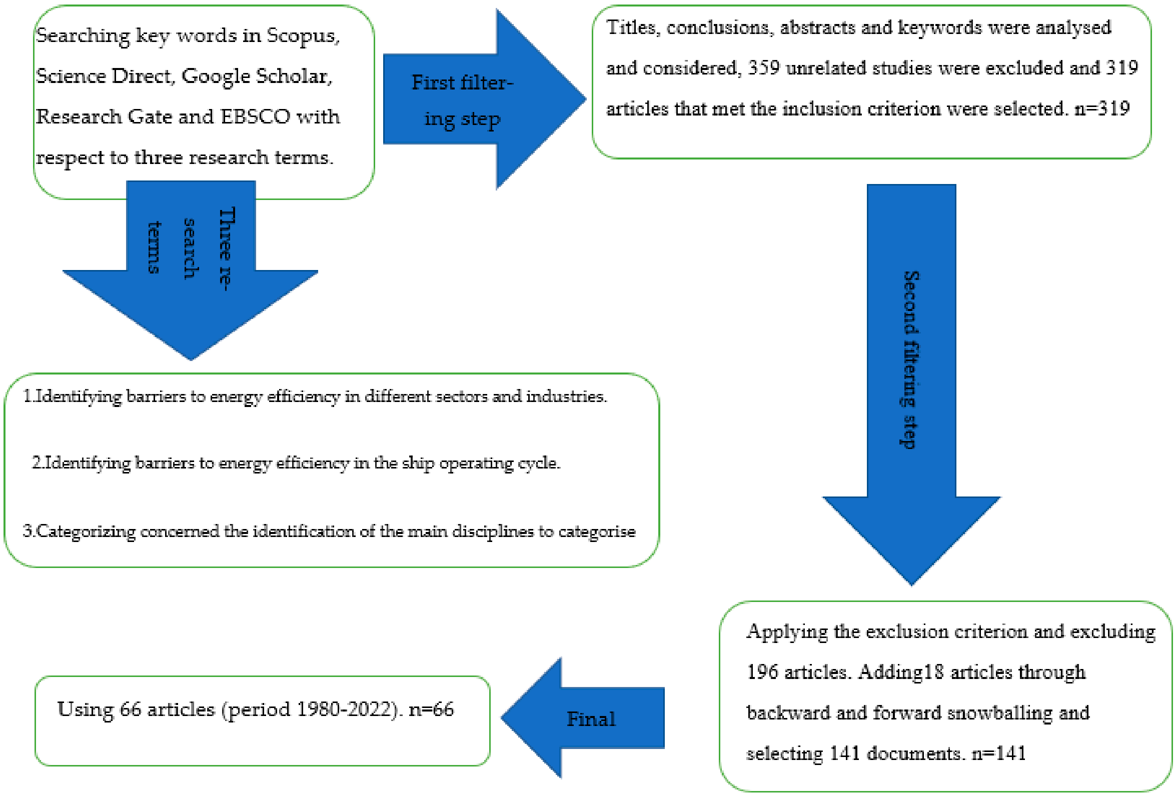

Figure 1. Systematic literature review.

In continue, the search terms were divided into three categories. The first category identified barriers to energy efficiency in different sectors and industries, the second category related to barriers to energy efficiency in the ship operating cycle and the third category identified the main disciplines to categorize barriers to energy efficiency in the ship operating cycle.

Filtering Phase

A total of 678 works in three categories were included. To select the best related articles, two criteria for inclusion and exclusion were considered (see Table 4). In the first filtering step, where titles, conclusions, abstracts and keywords were analyzed and considered, 359 unrelated studies were excluded and only 319 articles that met the inclusion criterion were selected. In the second filtering step, the exclusion criterion was applied, and after reading and analyzing the whole text, 196 articles were excluded that did not explicitly contribute to the development of energy-saving in the ship operation cycle. In addition, 18 articles were included by snowballing backwards and forwards and a total of 141 documents were selected and 66 of these (period 1980–2022) were used. The categorized barriers to energy efficiency (from the list in Phase 2) are shown in Figure 2 in five disciplines.

Table 4. Inclusion and exclusion criteria.

Criterion	Criterion One	Criterion Two
	Peer-reviewed articles and high-quality conference papers, books, industrial and technical reports, which are relevant to research questions and address energy efficiency.	Duplicate articles, non-peer-reviewed articles, low-quality industrial and technical reports, and articles that are not totally covered and improved energy efficiency.

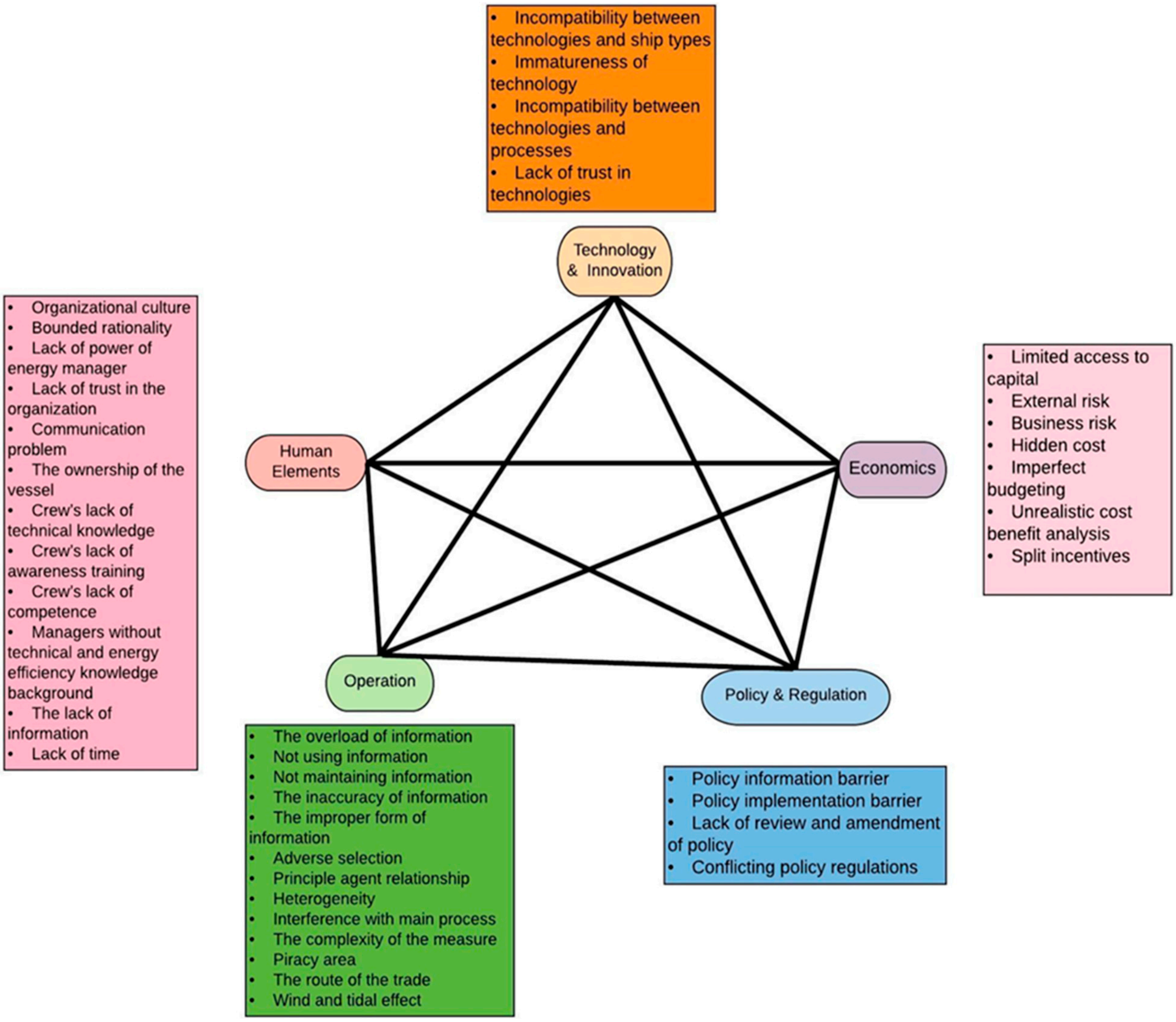

Figure 2. Categorization of key barriers in ships' operation cycle. Resource: [16,19,20,32,37,47,51–63].

3.2. Develop a Holistic, Systematic and Interdisciplinary Framework

A conceptual, holistic, systematic and transdisciplinary framework developed by the authors in Vakili et al. [13] was used to identify the barriers in the maritime business cycle. The proposed framework was adopted based on the priority areas of a shipping company's DM operations. Figure 3 shows how to recognize and rank the barriers to energy efficiency in the maritime business cycle. It consists of two steps: forward planning and backward planning. The forward planning consists of five main steps, namely "goal formulation", "system analysis", "scenario building", "multi-criteria assessment" and "strategy building".

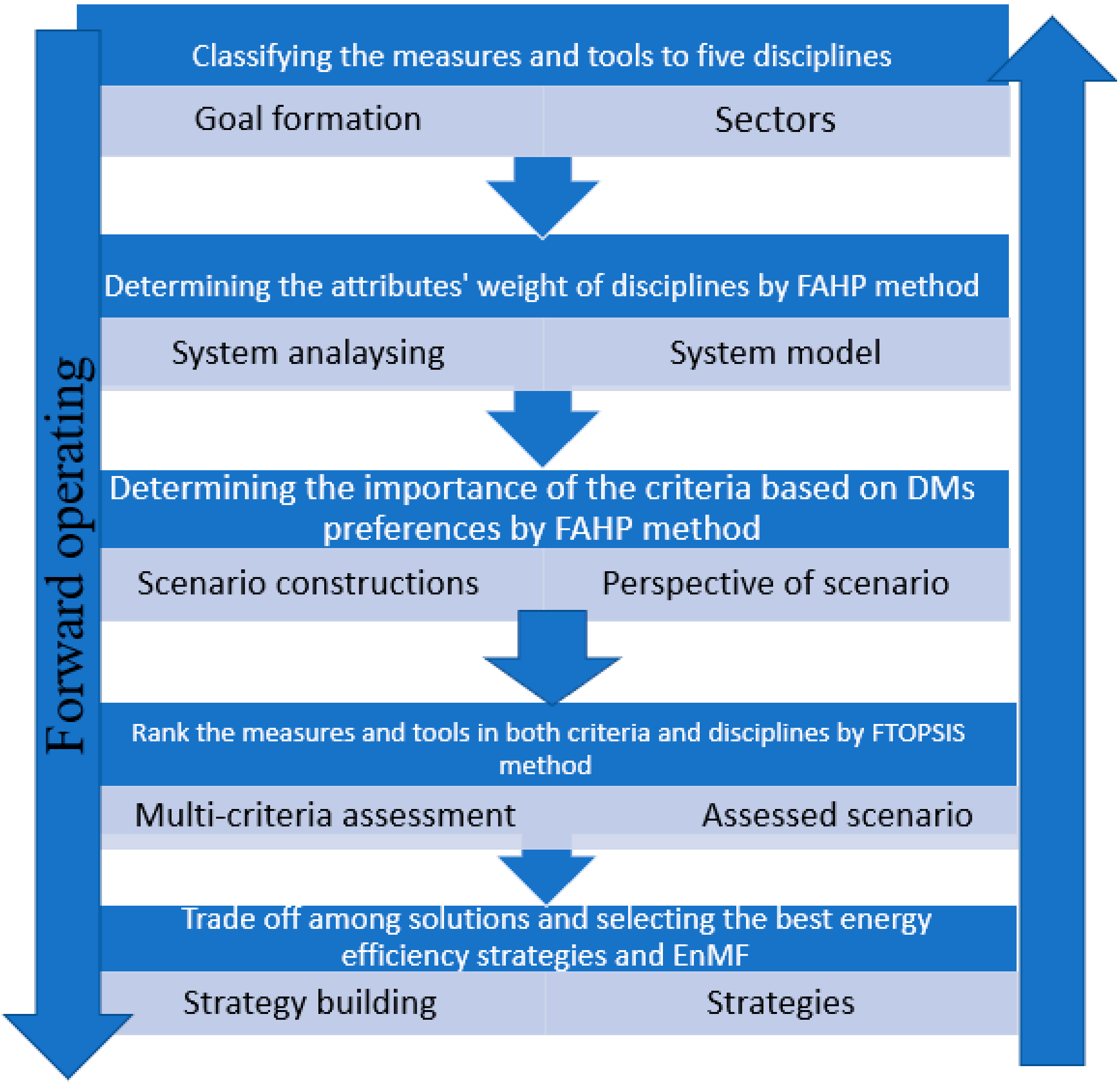

Figure 3. Transdisciplinary approach to design and develop the framework.

The framework starts with "goal formulation". In this phase, disciplines are identified and selected by the managers and barriers to energy efficiency are classified within these disciplines. In this study, five disciplines have been selected as the main disciplines: technology and innovation, policy and regulation, operations, economics and human factors; however, depending on the priorities of the decision makers, the disciplines may change.

In the "systems analysis", which is the second step, the first manager can use any MCDM. In this study, the FAHP method was utilized to show the importance of the characteristics of the disciplines. "Scenario construction" is the third step in the creation of the framework. In this step, managers use the FAHP method to elaborate on the importance of the criteria. The fourth step is the "multi-criteria assessment". In this step, using the results of steps two and three and the FTOPSIS method, managers can rank the obstacles in terms of both criteria and disciplines. "Strategy formation" is the final step in the framework. After applying the previous steps, the implementing manager has a better understanding of the type and importance of the barriers from different perspectives and, by developing causes, can make a rational decision to overcome the barriers to energy efficiency. The MCDM methods used, i.e., FAHP and FTOPSIS in this study, are explained in Appendix A.

4. Results and Discussions

Case study

To prove the functionality of the framework, a case study was conducted for a shipping company. Interviews were performed with five senior managers of an Iranian shipping company (ISC). ISC is active in inland water ways transportation, deep-sea shipping, coastal shipping and offshore projects and has various types of large and small vessels. In order to gain a better perspective in identifying the barriers to energy efficiency within the company, five key managers were selected who play a crucial role in improving energy efficiency both on board the vessels and in the office. An experienced captain and chief engineer of the fleet were selected as they are the key people responsible for the energy efficiency measures on board the vessels, as well as the head of fleet operations, the head of fleet engineering and the company's managing director, who have an important role in improving energy efficiency in the fleet. Figure 3 shows the application of the ISC framework and the steps have been summarized and the results are presented in Tables 5–8.

Table 5. Ranking of disciplines.

Companies \ Disciplines	Human Element	Operation	Technology & Innovation	Policy & Regulation	Economics
ISY	0.038	0.166	0.170	0.177	0.448

Table 6. Ranking of criteria.

Company \ Criteria	Severity of Barriers	Simplicity of Barriers Removal	Impact of Barriers Removal Energy Efficiency	Impact of Barriers Removal to Economic Performance
ISY	0.112	0.302	0.440	0.145

4.1. Goal information

The classification developed in the study is presented in Figure 2. The barriers were classified into five disciplines for ISC.

4.2. System Analyzing

Figure 4 demonstrates the weight of disciplines and Table 5 shows the priorities of ISCs. In the second step, "system analysis", based on DMs' priorities, the weight of attributes for the disciplines for ISCs was determined by applying the FAHP. As shown in Table 5, economics (0.448) was the most crucial discipline for ISCs. While policy and regulation (0.177) were the second most prioritized discipline for ISC, technology and innovation with a close weight (0.170) to policy and regulation was the third most prioritized discipline for ISC. Operations (0.166) was identified as the fourth-highest priority for the case firm and Human Factors (0.038) was identified as the least important discipline in the cases. The analysis showed that there was a serious imbalance between some of the disciplines (Figure 4). For example, the importance of the first priority (finance) was about 12 times higher than the least priority (human factors) in the ISC; however, the importance of three other disciplines (technology and innovation, operations, policy and regulation) was close to each other.

Table 7. Ranking of the ISC energy efficiency barriers in each discipline.

Barriers	T1	T2	T3	T4	E1	E2	E3	E4	E5	E6	E7	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	P1	P2	P3	P4
Ranking	1	3	4	2	2	7	4	5	6	3	1	12	10	11	9	6	1	8	4	2	5	3	7	13	6	2	8	10	9	12	7	3	1	5	4	11	2	1	3	4

Table 8. Final ranking of energy efficiency barriers in ISC.

Barriers	T1	T2	T3	T4	E1	E2	E3	E4	E5	E6	E7	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	P1	P2	P3	P4
Ranking	8	12	17	13	4	35	10	22	6	11	3	38	31	36	29	20	1	28	9	7	16	5	27	40	39	37	34	32	30	26	25	24	23	21	19	18	15	2	14	33

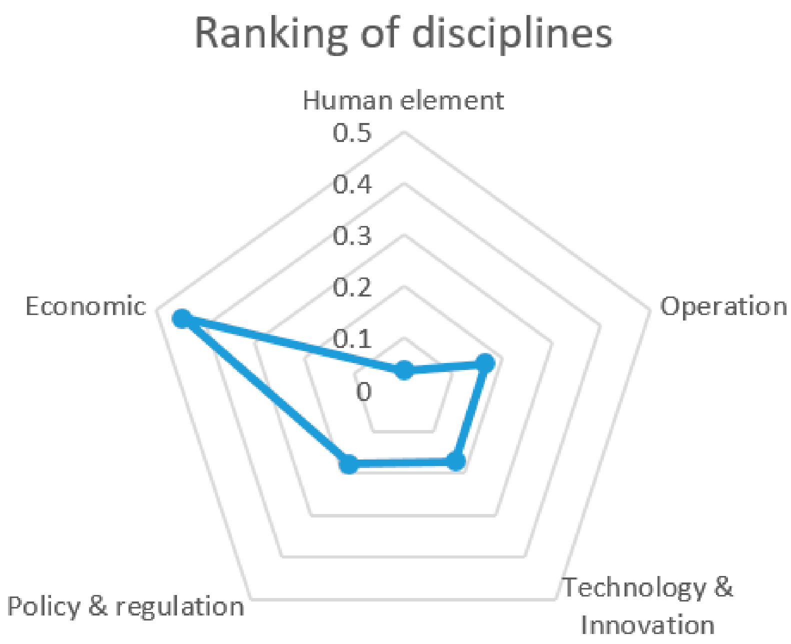

Figure 4. Weight of disciplines.

4.3. Scenario Construction

Figure 5 shows the weighting of the criteria. Scenario building was the third phase in the execution of the framework. Four criteria were considered in this phase (see Table 5). The goal was to check whether the criteria mentioned have the same importance in the five disciplines. The ISC managers can make a matrix for comparative weighting if the criteria have different importance in each discipline [12]. Respondents were questioned which criteria were most important to them in overcoming barriers. To analyze the interviews, the FAHP method was used in this phase. See Equations (A1)–(A9) in Appendix A.

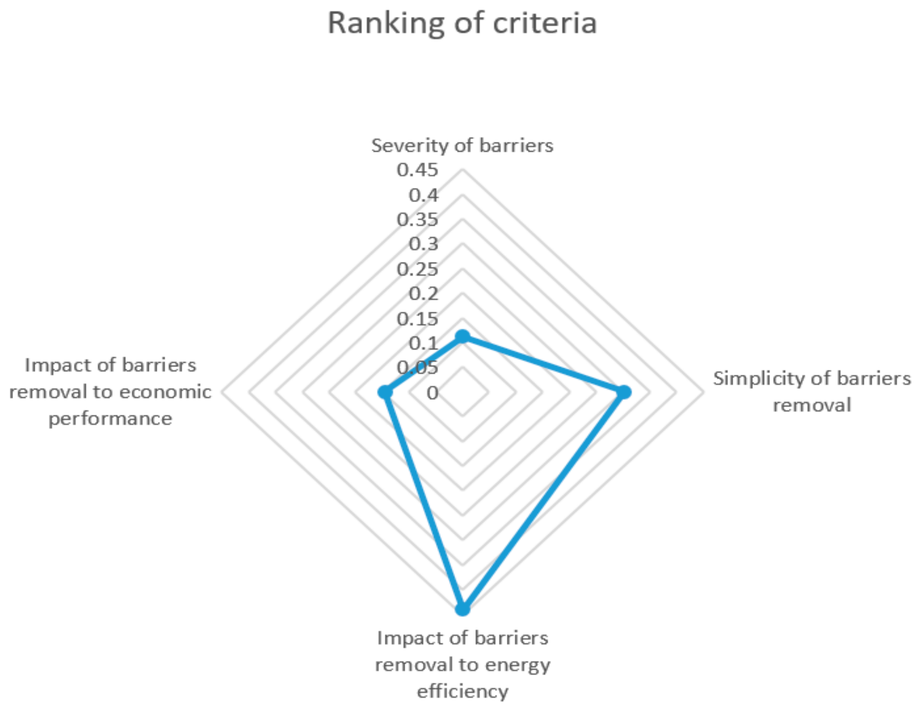

Figure 5. Weight of criteria.

As demonstrated in Table 6, the impact of removing barriers on energy efficiency (0.440) had the highest importance for company DM. This criterion was four times more important than the least important criterion (severity of barriers (0.112)). The second-highest priority for ISCs was the ease of removing barriers (0.302), and the impact of removing barriers on economic performance (0.145) was the third-highest priority (Figure 5).

4.4. Mcdm Assessment

The fourth step of the framework was the "MCDM assessment". In this step, the DMs of the case companies were able to rank the barriers to energy efficiency using the weighting of both disciplines and criteria and using the FTOPSIS methodology (Equations (A10)–(A16), see Appendix A), using each discipline and overall. Table 7 shows the result of the analysis and the ranking of the energy efficiency barriers within each discipline and Table 8 shows the final ranking of the energy efficiency barriers in the ISC.

Ranking of ISC's Barriers

Table 7 shows the ranking of the barriers within each discipline for the case study.

- Technology and innovation barriers

Figure 6 shows the closeness coefficient for technology and innovation discipline." Incompatibility between technology and vessel types", "lack of trust in technology" and "immaturity of technology" were the main barriers to "technology and innovation discipline". Some technologies are not suitable for all types of vessels. For example, the most efficient propeller type is different for each type of vessel. This is also due to "heterogeneity", "adverse selection" [34] and "incomplete information" [47].

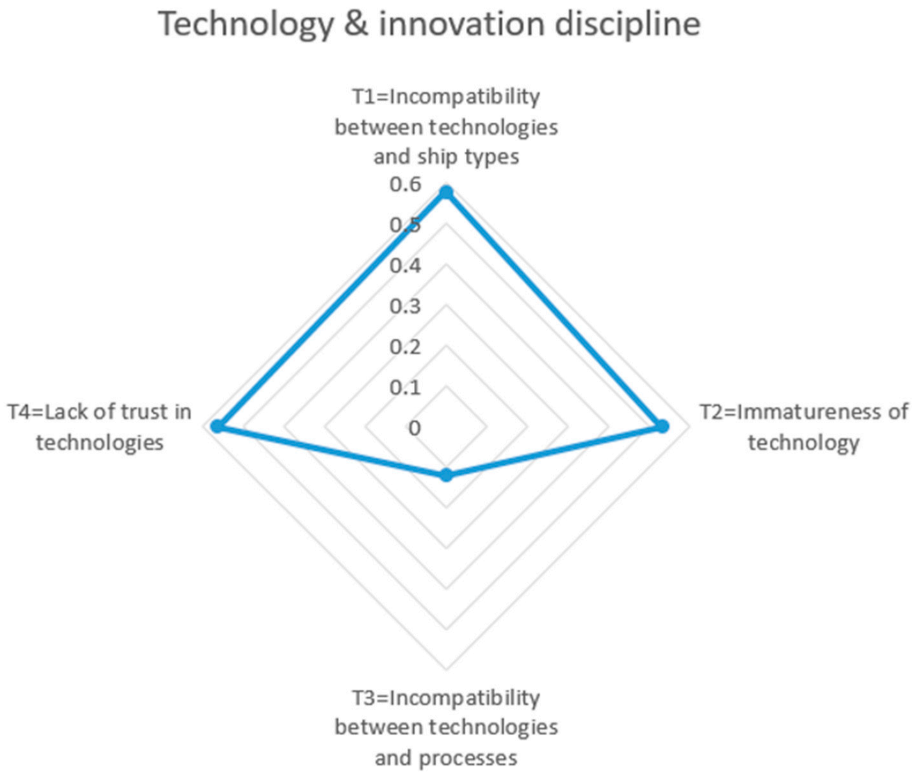

Figure 6. Closeness coefficient for technology and innovation discipline.

"Lack of confidence in the technology" is due to the credibility and trust in the source of information [33,34] and "immaturity of the technology", as the new technology, e.g., wind sails and bubble curtains, needs to be developed and evaluated in the future in order to confirm its maturity. Interviewees stated that they are reluctant to take an investment risk for immature technologies. The reviewers pointed out that although wind propulsion systems and wing sails have received attention in the industry, the related technologies have not been sufficiently developed and need to be further developed to be introduced to the market. In addition, they stressed that the said technology is not suitable for all trade lines with respect to the availability of wind and that investment in such technology will increase the "business risk" [61] for the company, which they cannot bear such risks in the current financial crisis. Another example given by interviewees was the use of carbon capture and storage (CCUS) on board ships. They pointed out that CCUS has been presented as a future technology to reduce CO_2 emissions in the maritime industry, but that there are significant technical, financial and legal barriers to implementing the technology on board ships and that there is no confidence in its effectiveness, "lack of confidence in the technology". In addition, the technology is not suitable for all types of ships "incompatibility between technologies and ship types" and "heterogeneity".

- Economic barriers

Figure 7 shows the closeness coefficient for economic discipline. The company has many vessels that are chartered and claim that the benefits of the investment in improving the energy efficiency of the vessels are not passed back to the company, but that it is the charterer who benefits from the investment. It is back to the "split incentive" barrier [37,53], which means that the investor cannot benefit from an investment in energy efficiency. In the case of charterers, they are not willing to invest in capital costs, which can lead to hidden investments. In addition, interviewees claim that energy efficiency measures are expensive and that they have "limited access to capital" (the second main barrier to energy efficiency) [20,21]. They also claim that "limited access to capital" is due to the international sanctions against the company, which leads to poor budgeting and puts energy efficiency at a lower place in the company's priorities [13,24].

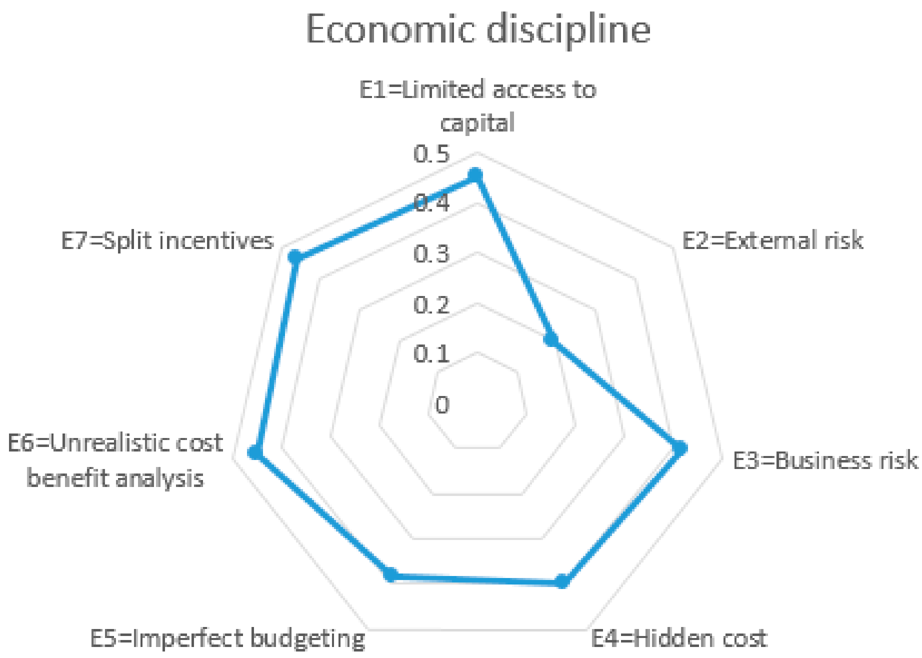

Figure 7. Closeness coefficient for economic discipline.

"Unrealistic cost-benefit analysis" and "imperfect budgeting" as the third and sixth-highest priority barriers are due to barriers of market failure and poor information [54,64]. "Unrealistic cost-benefit analysis" can hinder investments in energy efficiency measures [13]. For example, the extra energy cost of air bubble curtains and the cost of extra compressors may be ignored in the analysis. In addition, "imperfect budgeting" is linked to limited "access to capital" and this is more prominent because international sanctions have left the company without access to capital. The fourth and seventh-highest priorities, i.e., "business risk" and "external risk", are related to barriers to failure outside the market that may also hinder energy efficiency investments [30]. Finally, the hidden cost was the fifth-highest priority for the company. The hidden cost is related to the overhead costs of contracting and information gathering [14]. This is more serious in small shipping companies that do not have access to complete information in comparison to large fleets. Staff training, staffing needs and opportunity costs for investments are other types of hidden costs that may occur in shipping companies [47].

- Operation Barriers

Economic and contractual constraints among ship owner, operator and charterer on the speed and route of voyages caused ship operators to often be unable to use certain types of optimization or benefit from fuel-saving technologies. Figure 8 shows the closeness coefficient for operation discipline. "Adverse selection", "interference in the main process" and "piracy area" were the main energy efficiency barriers in the discipline. "Adverse selection" is a barrier to market failure and can lead to disruption of the main process and vessel operations. "Adverse selection" can occur if two parties are asymmetrical [59,63] and, therefore, it can lead to decisions being made solely on the basis of shape, color or price and less attention being paid to the effectiveness of the technology [37,47]. Since the energy efficiency potential of the technology (especially in the maritime cluster) is not tangible, most decision makers choose the technology on the basis of visible aspects such as price [55]. This is due to the lack of information from DM's companies who are not familiar with updated information and new technologies. It is also related to "heterogeneity" (fourth main barrier) as it may lead to “adverse selection” [50,61] of energy efficiency measures that are not appropriate for the type, size and route of the vessel. For example, investments in sailing for vessels not sailing in the windy area of the “trade route (seventh main barrier)” is an example of “adverse selection” and “heterogeneity”. In addition, the leaders argued that energy-efficient technologies are not suitable for all types of vessels and may be cost-effective for some vessels and not for others’ “heterogeneity”. As an example, the manager stated that waste heat recovery was effective for their ocean-going vessels, but not suitable for their offshore fleet.

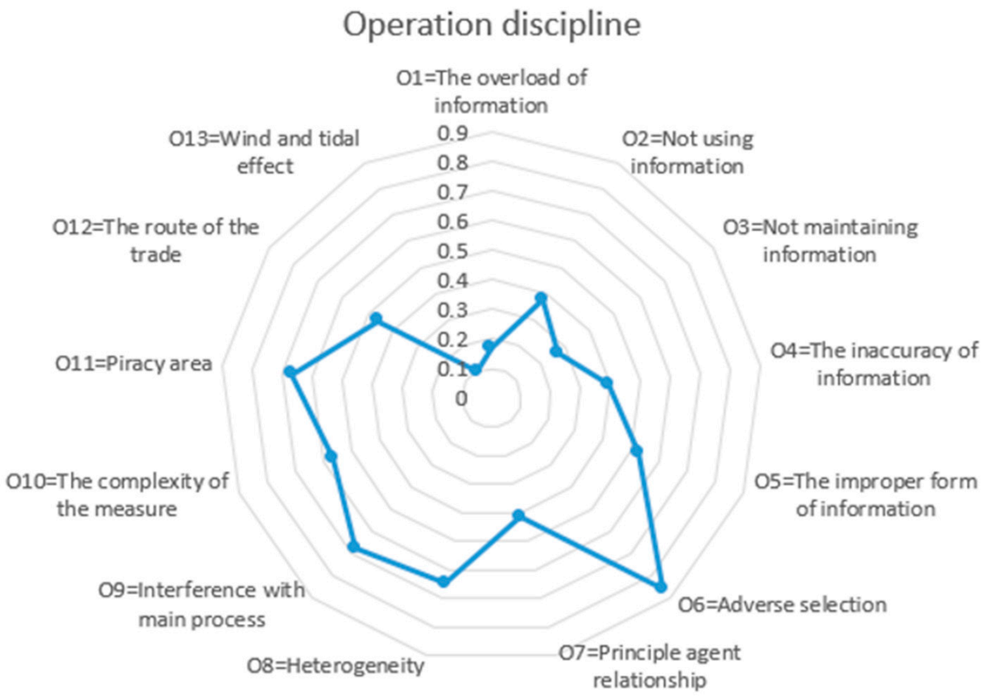

Figure 8. Closeness coefficient for operation discipline.

Furthermore, the implementation of certain technologies affects the main operation of the vessels. Company managers were reluctant to adopt technologies that require the vessel to be decommissioned (especially during peak periods), such as the installation of wing sails and waste heat recovery. As the company has vessels sailing in” piracy areas”, this becomes one of the company’s top priorities. It is also linked to the “trade route (seventh biggest obstacle)”. All interviewees clearly stated that the safety of the ships sailing in pirate areas is a higher priority than improving energy efficiency.

“Complexity of measures” and “inadequate information” were ranked fifth and sixth, respectively. “Complexity of the measure” may hinder investment in energy efficiency measures as more complex measures require more knowledgeable and trained personnel [41,42]. When the technology becomes complex, higher installation costs and more skilled personnel are required [53,57]. For example, installing digital twin technology is expensive and its effectiveness depends on the skills and knowledge of staff, or it is necessary to establish additional degrees on board ships and in offices and to train staff to become familiar with the technology’s requirements in order to gain maximum benefit from its introduction [14]. In addition, complexity can lead to time-consuming use of the technology and “disruption of the main process” and staff tasks [18]. The “principal-agent relationship” (eighth-highest priority) is a barrier to market failure. Due to lack of information and conflicts of interest, the ship owner may not follow what the agent is doing or may have a lack of trust in the agent [59], which may lead to energy efficiency measures being ignored. For example, there may be a conflict between the charterer and the ship-owner in presenting the vessel on a particular date in a particular port. “Incorrect information” (ninth-highest priority) is a barrier that is not a market failure [16]. Finally, "not using information" (tenth-highest barrier) and "not maintaining information" (eleventh-highest barrier) are behavioral barriers [37] and "information overload" (twelfth-highest barrier) is an organizational barrier [51]. The analysis of the questionnaire shows that most of the information-related barriers were the least important for the enterprise.

- Human element barriers

Figure 9 shows the closeness coefficient for human element discipline. "Crew's lack of technical knowledge (competence)", "bounded rationality" and "crew's lack of awareness training" were the main barriers to ISC's human elements. A skilled, well-trained and aware crew can increase efficiency on board ships [47]. Even changing the crew (especially high-ranking personnel, e.g., captain and chief engineer) can affect the efficiency of the ship. In addition, trained and knowledgeable personnel are required for the proper use of the installed technology [62]; therefore, staff training and familiarity with the energy-efficient technologies on board the vessels, as well as an improved energy efficiency culture within the company, can affect the energy efficiency of the fleet. "Bounded rationality" (the second most important barrier) is a type of behavioral barrier [27]. Rather than making the optimal decision based on the scarcity of information, executives make decisions according to rules of thumb and seek to make a satisfying decision [33].

"Lack of information" (fourth-highest priority) can act as a barrier to improving energy efficiency in the firm [42]; however, it can be overcome through staff training [62] and by sharing information and experiences between all vessels and staff. Learning from other companies' experiences can improve energy efficiency within the company. "Managers without technical knowledge and background" (fifth-most prioritized barrier) can hinder investment in energy efficiency in shipping companies. It is important that managers have a technical background and are familiar with energy efficiency measures [58]. "Organisational culture" (sixth-most prioritized barrier) plays a crucial role in improving energy efficiency in an organization. Raising staff awareness of environmental issues, environmental problems and related issues can promote the organization's values of protecting the environment and can reduce the energy efficiency gap in the company [30].

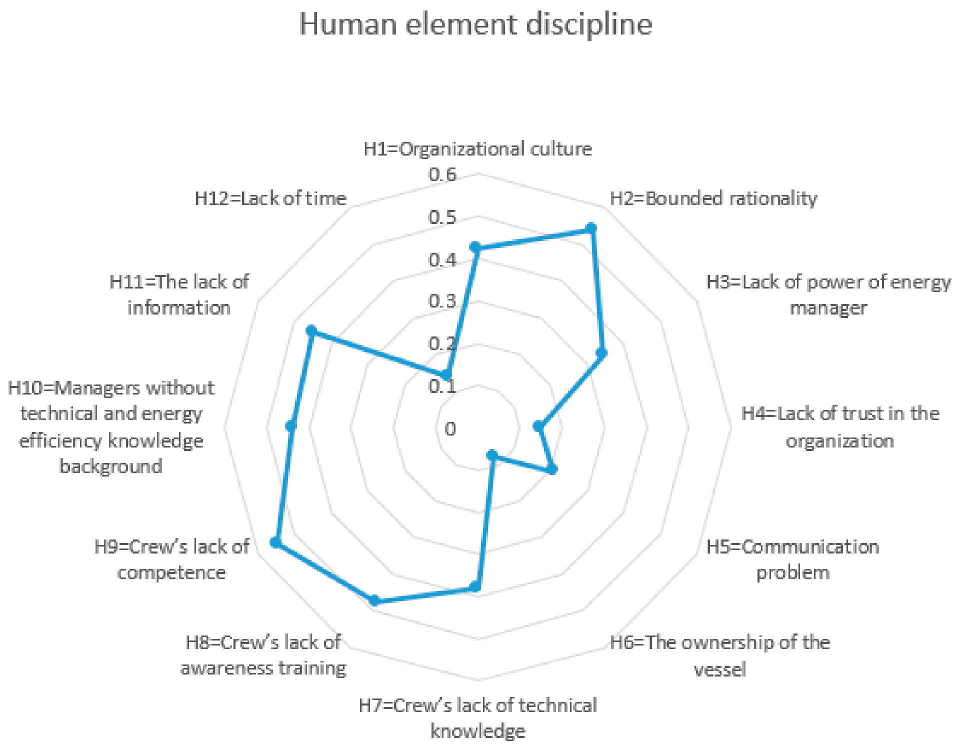

Figure 9. Closeness coefficient for human element discipline.

"Lack of power of the energy manager", "communication problems" and "lack of trust in the organization" were ranked as eight, nine and ten, respectively, and are supported by organizational barriers [32,33]. The interviewees mentioned that the company does not have a specific and classical energy manager and that one of the employees in the technical department is responsible for monitoring the fleet's fuel consumption, and that he is under the supervision of the head of the department. They pointed out that this creates conflicts between departments and leads to a lower priority of energy issues within the company [16]. In addition, "communication problems" can act as a barrier when different people with different backgrounds view the issue from different perspectives [13], which can lead to investments in energy efficiency being ignored.

"Lack of trust" in the organization can act as a barrier (the tenth-most important barrier for the company) if it leads to disagreement on the implementation of energy efficiency measures [37,65]. "Lack of time" (eleventh-highest priority barrier) can occur if staff are overloaded with tasks, which can lead to an increase in the energy efficiency gap in the fleet. Case company interviewees highlighted that due to the financial crisis, the company has other priorities [53] and that investments in improving the energy efficiency of the fleet are at the bottom of the agenda. Vessel ownership (the twelfth biggest barrier) may also be hindering investment in energy efficiency improvements in the fleet, as DMs recognized that they have more time and interest in investing in the vessels they own rather than in those that are chartered.

- Policy and regulations barriers

The barrier to policy implementation was the main energy efficiency barrier for the company. As an example, DM's stated that they need capital to invest in energy efficiency in their fleet and order new ships, but due to national regulations and international sanctions, they cannot request loans from foreign banks. In addition, the implementation of certain policies and regulations may "disrupt the main process" and the operation of the vessels [41,43]. For example, the company has to embark special forces on its ships when they pass through a piracy-dominant area. This means deviating from the main route, which increases fuel consumption and extends the vessel's travel time. "Political information barriers" (second-most important barrier) may prevent investment in energy efficiency improvements in the company. Lack of staff information from company policy on energy efficiency measures on board the vessel, especially from senior staff such as the captain and chief engineer, can reduce fleet efficiency. Appropriate communication between the office and ship personnel is critical to ensure that all policies and regulations are adequately understood and implemented on board [42]. It is important that the company provides its staff with short, medium and long-term energy strategies. "Lack of review and amendment of policies" was considered to be the third most important obstacle for the company in terms of discipline on policies and regulations. This can act as a barrier if the company does not comply with the new regulations required on energy efficiency measures [43]. It is important that a team in the company complies with local, regional and international regulations on energy efficiency measures. In addition, "conflicting policies" can also hinder investment in improved energy efficiency measures on board ships. One example is that preventing hull cleaning in ports leads to an unsightly and resistant hull, resulting in increased fuel consumption [47].

4.5. Strategy Building

In the final phase, which is "Strategy formation", the responsible directors can rank the barriers to energy efficiency in their organization according to their priorities. At this stage, the disciplines' weights from Section 4.2, were applied. FTOPSIS Equations ((A10)–(A16) in Appendix A) are used for ranking the barriers. Table 8 demonstrates the final ranking of the energy efficiency barriers for the studied company. Based on the result of the analysis, ISC DMs can overcome bounded rationality [30,37] and can make a rational decision on investments in energy efficiency improvement measures [13].

Measures to Overcome the Barriers

- Disciplines

The weighting of the disciplines has a considerable impact on the hierarchy of barriers to energy efficiency. The analysis shows that there is a large gap between the most important discipline "economics" and the least important "human element". The former discipline is 12 times more important than the latter; however, there was less variation in the other disciplines, namely 'operations', 'technology and innovation' and 'policy and regulation'. It is recommended that companies pay more attention to the human factor as the discipline is an important factor in improving energy efficiency [13,33]. The lack of attention to the human factor is reflected in the ranking of the barriers to the human factor, which led to "crew lack of skills" and "crew lack of awareness training" being ranked as the highest barriers in the disciplines. Training and increasing environmental protection awareness of staff can eliminate "crew lack of competence", "crew lack of awareness training", "managers' lack of knowledge of technology and energy efficiency" and "energy managers' lack of power" [62]. In addition, it will foster both individual and corporate culture to protect the environment and can remove the associated behavioral barriers.

- Technology

"Incompatibility between technology and vessel types", "immaturity of the technology" and "lack of confidence in the technology" were ranked as the eighth, twelfth and thirteenth most important barriers in the case study, respectively. The rapid transition to carbon reduction and the introduction of different technologies without proven results create uncertainty among ship-owners to invest in energy efficiency technologies [45]. It is important that ship managers and executives have technical knowledge and awareness of energy efficiency measures about the proposed technologies on the market [41]. This requires managers and directors to be well educated on the subject and to receive specific, vivid, simple and personalized information in order to make a rational decision [18]. In addition, unsuitable and immature technologies can be tested in pilot projects. Although the use of immature technologies increases the technical risk [53], a smart contract and collaboration with technology manufacturers can lead to a win–win deal [47].

- Economic

"Split incentives", "limited access to capital" and "poor budgeting" were the third, fourth and sixth biggest energy efficiency for the company. "Split incentives" is also related to "ownership of the vessel", which is linked to charter vessels where the company is paid for the technology and charters because the party was paying for the fuel benefits from the investment [43]. This could be reflected in charter contracts, for example, through higher charter fees for more efficient vessels, in a way that reduces the barriers to common incentives. In addition, cooperation with the Legal Department in providing appropriate charter contracts by taking into account the bunker adjustment freight may help to overcome the barrier.

"Limited access to capital" and "incomplete budgeting" are a consequence of the reduction in the company's activities due to international sanctions; however, appropriate budgeting and consideration of the company's priorities can mitigate the shortcomings in the energy efficiency of the company [13]. It is important that managers make a rational decision to improve energy efficiency within the company and that their priorities take into account measures that are easy to implement, such as slow steaming [8], and 'just in time'.

- Operation

Figure 10 shows the final ranking of energy efficiency barriers in ISC. "Adverse selection" was the main energy efficiency barrier for the company to improve energy efficiency and it is classified as an obstacle to market failure in the classical categorization [34]. In addition, "heterogeneity" was considered the ninth most important barrier in the firm and it is classified as a non-market failure barrier in the classical categorization [32,33]. By providing appropriate "form of information" (twentieth-highest barrier) and using the right (credibility and trust) form of information (specific, vivid, simple and personal (SVSP)) [30] and by overcoming "principle-agent relationship" (twenty-eighth highest barrier) and "information inaccuracy" (twenty-ninth highest barrier), managers can reduce "limited rationality" (the second-highest barrier, discipline of the human factor) and make an appropriate selection to improve the energy efficiency of the company and also the best technology with respect to the types and sizes of vessels [13].

- Human Element

The "human factor" was the least important discipline among the others. "Lack of time", "lack of information" and "managers lacking knowledge of technology and energy efficiency" were the top priorities for the company in eighteenth, nineteenth and twenty-first place. Seafarers' managers claimed that staff do not have enough time due to the workload on board ships, and office staff complained that they are overloaded with work and that energy efficiency cannot be placed among their top priorities. Although this can be solved by employing more staff both on board the vessels and in the office [47], it is proposed that an independent energy department be set up within the company and the head of the department must be independent, well-trained and have sufficient knowledge of the subject. In addition, it is necessary that the related manager has sufficient power in decision making among the directors.

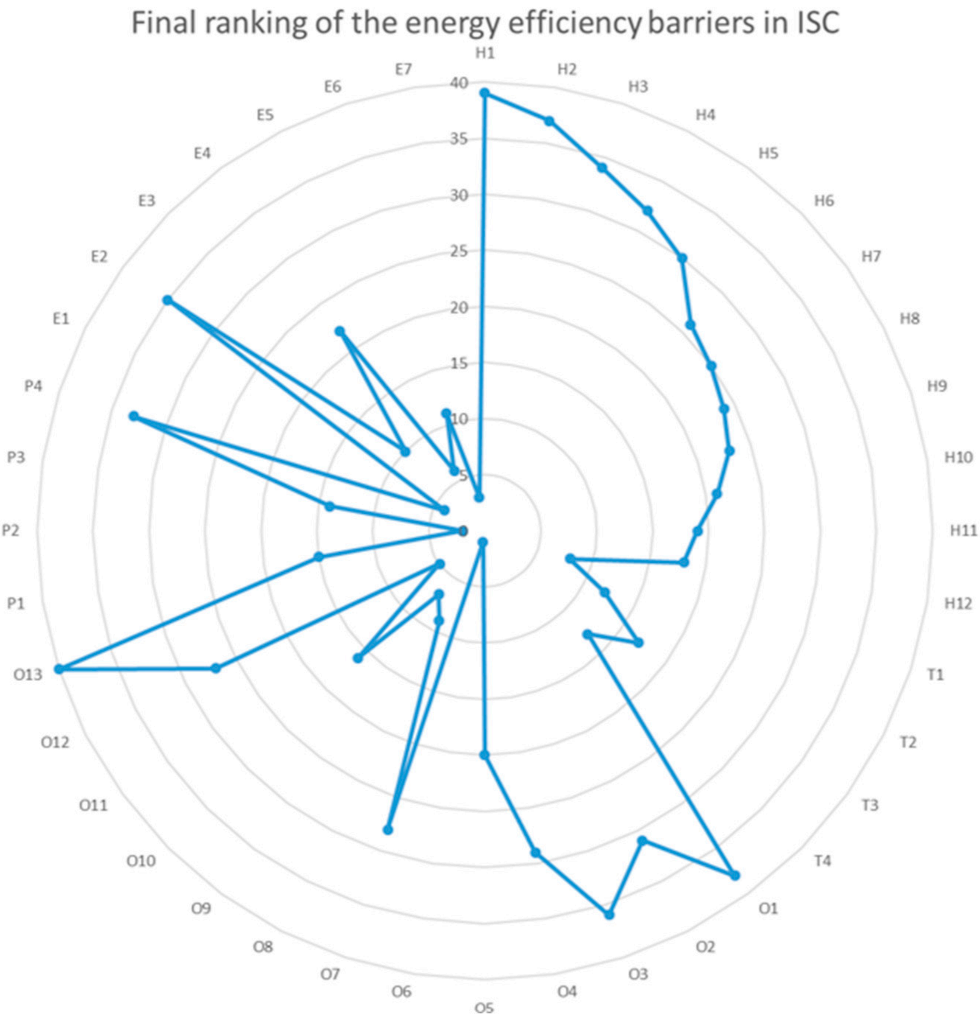

Figure 10. The final ranking of energy efficiency barriers in ISC.

- Policy and Regulations

"Policy implementation barrier" was the second-highest priority for the company. Implementing international sanctions against the company was the biggest challenge for the company in terms of accessing capital. Lack of access to capital led to improving energy efficiency being considered the lowest priority for the company. On the other hand, in order to maintain and promote its position in the competitive shipping market, the company has to comply with IMO's energy efficiency regulations such as the initial GHG strategy [3,12], which implies additional costs for the company; however, the complexity of the industry, the structure of the shipping sector and the relationship between stakeholders, e.g., the contracts between shipbuilders, ship owners and charterers, as well as the barriers to global monetary transactions, constitute an obstacle to the introduction of energy efficiency and technology [4]. In addition, parallel bilateral regulations will be improved at the regional level, such as the European Emissions Trading Scheme (ETS) for shipping, as shipping is sensitive and rapidly phasing out carbon. Interviewees pointed out that non-homogeneous policies and regulations make them more complicated to implement, and they prefer to have a homogeneous international regulation for shipping at IMO level.

- Summary

To confirm the validity of the suggested framework, a case study was undertaken in an Iranian shipping company and surveys were completed with five senior managers in the company. Four criteria were presented to them to prioritize the barriers, namely "how severe the barriers are", "how easy it is to remove the barriers", "how much impact the removal of the barriers has on energy efficiency" and "how much impact the removal of the barriers can have on the economic performance". By using FAHP and FTOPSIS, the prioritization of barriers was determined in each discipline and in overall aspects. The outcomes show that:

1. International sanctions have had a negative impact on investment and the implementation of energy efficiency measures, pushing energy efficiency improvements to the bottom of the agenda.
2. There was a significant difference in importance between the most important discipline "economics" and the least important one, i.e., "human factors"; however, the importance of the other three disciplines was close to each other.
3. In terms of criteria, the most important for DM was "impact of barriers removal to energy efficiency". "simplicity of barriers removal", "impact of barriers removal to economic performance" and "severity of barriers" were ranked in order of importance.
4. "Adverse selection" (operational discipline), "policy implementation" (policy and regulatory discipline), "split incentives" (economic discipline), "limited access to capital" (economic discipline) and "imperfect budgeting" were the first top priorities for the firm.

To overcome these energy efficiency barriers, their interrelationship must be taken into account [13]. A lack of attention to human factors can lead to a lack of awareness of the opportunities that can help improve energy efficiency [4]. Even if the international sanctions mean a downturn for the company, appropriate budgeting and consideration of priorities can help overcome the barriers to energy efficiency [12]. By paying more attention to behavioral barriers, such as "information form" and the use of the right form of information (credibility and trust) (specific, vivid, simple and personalized information (SVSP)) and "inaccuracy of information", DM managers can overcome "adverse selection" [54]. The company must have a strategic plan to overcome the challenges that may arise in improving the energy efficiency of the fleet due to the chartering of vessels and the regulatory differences that may arise during the decarbonization of international shipping. To overcome the challenges, it is important that the company considers having an independent energy department and a manager with sufficient authority.

5. Conclusions and Policy Implications

A holistic, systematic and transdisciplinary approach plays a crucial role in improving energy efficiency and reducing CO_2 emissions in shipping industry and not only industry stakeholders but also end-users must be prepared to pay additional costs for this transition. Overcoming barriers to energy efficiency requires taking into account the interrelationship, linkage and interaction of barriers, and considering the perspectives of different active actors. The aim of the study was to identify the barriers to energy efficiency in the operational phase of the ship's life cycle. The novelty of the study was that it classified the barriers to energy efficiency into five categories, i.e., operational, policy and regulatory, technological and innovation, human factors and economic, and proposes a holistic, systematic and transdisciplinary framework to identify shipping companies' barriers to energy efficiency and to analyze the relationship and interaction between the different barriers. The implementation of the framework leads to overcoming the barrier of limited rationality and helps company directors to make rational and optimal investment decisions to overcome energy efficiency barriers in companies and accelerate the carbon reduction in the company and fleet at the lowest possible cost in a clear atmosphere.

The IMO's initial greenhouse gas strategy aims to reduce absolute emissions by at least 50% by 2050 and to reduce carbon intensity by at least 40% and 70% by 2030 and 2050 respectively, all compared to 2008. Due to the fact that different states have not agreed on how ambitious the IMO's greenhouse gas emission targets are, there is still some uncertainty for ship-owners to invest in green technologies. Harmonized and consistent global rules and targets can remove the obstacle of "conflicting approaches" and accelerate investment in improved energy efficiency on board ships. In addition, the existence of different types of technologies to improve energy efficiency in the industry can lead to "adverse selection and limited rationality". It is important that ship-owners' managers take a holistic view of technology and choose the technology that is best suited to their fleet and individual vessels in order to overcome the "heterogeneity barrier" and prevent "incompatibility between technologies and vessel types".

Based on the analysis of the interviews, the company needs to change its structure and improve its "organizational culture" regarding energy efficiency aspects. Considering the creation of an independent energy efficiency department with appropriate "powers" can overcome the barriers to energy efficiency. The department must design, develop and implement the company's short, medium and long-term "energy strategy", both for the fleet and the offices. The department's staff must have the necessary "knowledge" and have "technical and energy efficiency skills". In addition, the department must improve the company's "knowledge, skills and awareness" both onshore and on board the vessels and have a vision to improve the energy efficiency "culture" within the company.

On the other hand, technology suppliers must provide end-users (shipping companies) with sufficient "information" about the technology. Providing information (specific, live, simple and personalized information (SVSP)) can help to overcome the "limited rationality", and subsequently, an appropriate choice of technology can reduce the "external risk and business risk", and avoid choosing "immature technology". Taking into account the mentioned measures can help the company to overcome "limited access to capital" and use the allocated budget efficiently. The second fact that must be considered is that it is important that all departments and staff, both on board and in the office, work together to overcome energy efficiency barriers. Supporting the legal department in providing appropriate charter agreements to obtain benefits from energy efficiency investments in the fleet and overcoming "split incentives" is another benefit of interdepartmental cooperation to improve energy efficiency on board vessels and obtain the financial benefits of such investments.

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and editing: S.V.V., A.I.Ö., F.B. and D.D.; visualization: S.V.V., F.B., D.D. and A.I.Ö.; supervision: S.V.V., F.B., D.D. and A.I.Ö. All authors have read and agreed to the published version of the manuscript.

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Appendix A. The Utilized MCDM Methods

Appendix A.1. Fuzzy Analytical Hierarchy Process (FAHP)

In this study, the FAHP method was used to provide a weighting of attributes for the main disciplines and criteria. Table A1 shows the equations that used in this study.

Table A1. Equations that are used in FAHP method.

Number and Description of the Equations	Equation	
1-Sum of a fuzzy number $\oplus$	$\tilde{n}A \oplus \tilde{n}B = (aA+aB, bA+bB, cA+cB)$	(A1)
2-Multiplication of a fuzzy number $\otimes$	$\tilde{n}A \otimes \tilde{n}B = (aA\times aB, bA\times bB, cA\times cB)$	(A2)
3-Division of a fuzzy number $\varnothing$	$\tilde{n}A \varnothing \tilde{n}B = (aA/aB, bA/bB, cA/cB)$	(A3)
4-Subtraction of a fuzzy number θ	$\tilde{n}A\ \theta\ \tilde{n}B = (aA-aB, bA-bB, cA-cB)$	(A4)
5-Reciprocal of a fuzzy number	$X\tilde{n}\ a - 1 = (a,b,c) - 1 = (1/c, 1/b, 1/a)$	(A5)
6-In this research, the geometric mean technique [66] was employed to perform the data analysis to compute the fuzzy values.	$Ƒ = (\tilde{n}i,1 \otimes \tilde{n}i,2 \otimes \ldots\ \tilde{n}i,n)\ 1/n$ $= ((a\ i,1 \times a\ i,2 \times a\ i,3 \ldots \times a\ i,n)\ 1/n,$ $(b\ i,1 \times b\ i,2 \times b,i,3 \ldots \times b\ i,n)\ 1/n,$ $(c\ i,1 \times c\ i,2 \times c\ i,3 \ldots \times c\ i,n)\ 1/n)$	(A6)
7-ω i =fuzzy weight of the *i*th event	$\omega\ i = \frac{Ƒi}{Ƒ1 \oplus Ƒ2 \ldots\ldots \oplus Ƒn}$	(A7)
8-Ƒ*i* =geometric mean of the *i*th row	$DF\ \omega I = \frac{[(ci-ai)+(bi-ai)]}{3+ai}$	(A8)
9-Difuzzified (DF) mean of the weights	Then $Wi = \frac{DF\ \omega i}{\sum DF \omega i}$	(A9)

Appendix A.2. Fuzzy TOPSIS

Table A2 shows the equations that have been used in the FTOPSIS method.

Table A2. Equations that are used in FTOPSIS method.

Number and Description of the Equations	Equation	
10-Ʊij K is the rating of the Kth DM	$Ʊij = \frac{1}{K} [Ʊij\ 1\ (+)\ Ʊij\ 2\ (+) \ldots (+) Ʊij\ K]$	(A10)
11-ωj K is importance weight of the Kth DM	$\omega j = \frac{1}{K} [\ \omega j\ 1\ (+)\ \omega j\ 2\ (+) \ldots (+)\ \omega j\ K\ ]$	(A11)
12-Fuzzy decision matrix	$\acute{R} = [\acute{r}ij]m\times n,$	(A12)
13-Normalized fuzzy decision matrix	$\tilde{V} = [\tilde{v}\ ij]mxn,\ i = 1,2,\ldots,\ m,\ j = 1,2,\ldots,\ n$ (8), where $\tilde{v}ij = \acute{r}ij\ (.)\ \omega j$	(A13)
14-Distance from Positive ideal solution	$d_i^* = \sum_{j=1}^{n} d(\tilde{v}ij,\ \tilde{v}^* i)\ i = 1,2,\ldots,m$	(A14)
15-Distance from negative ideal solution	$d_i^- = \sum_{j=1}^{n} d(\tilde{v}ij,\ \tilde{v}^- j)\ i = 1,2,\ldots,m$	(A15)
16-Closeness co-efficient	$CC_i = \frac{d_i^-}{d_i^* + d_i^-},\ i = 1,2,\ldots,m$	(A16)

Figure A1 demonstrates the hierarchical priorities of the barriers to energy efficiency for ISC.

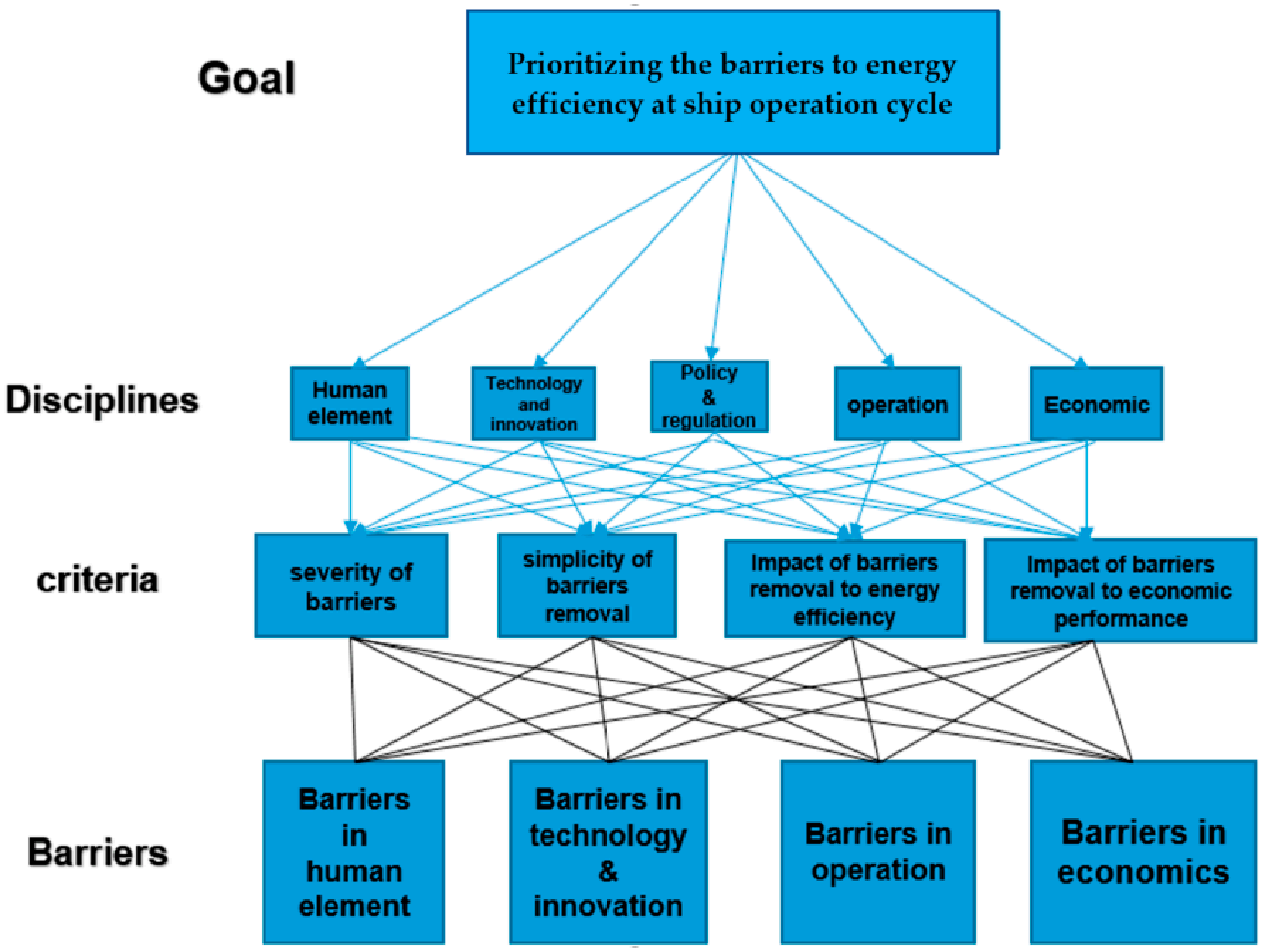

Figure A1. The hierarchical prioritizing of the barriers to energy efficiency by AHP for a shipyard.

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