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Decision-Making on the Selection of Clean Energy Technology for Green Ships Based on the Rough Set and TOPSIS Method

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Abstract: In the context of the decarbonization of the shipping industry, the application of clean energy technologies is a catalyst for decarbonization. With the number of potential clean energy technologies expanding, the uncertainties in terms of technology maturity, policy regulation, and economics make clean energy technologies decision much more difficult. Therefore, it is urgent to establish a clean energy technology selection scenario for the green ship industry to assist shipowners in decision-making. Based on this, a technology selection model based on rough set (RS) and approximate ideal solution ranking (TOPSIS) is constructed. Using RS to reduce the evaluation index and calculate the weight can avoid the one-sidedness of subjective weighting. Using the TOPSIS method to rank alternatives. This paper selects seven clean energy technology alternatives, namely LNG power, LPG power, methanol power, HVO power, pure battery power, hydrogen fuel cell, and ammonia fuel cell, respectively, as the evaluation objects. Taking two types of vessels as examples, it is concluded that LNG power technology is suitable for large coastal ro-ro passenger vessels, and pure battery power technology is suitable for small inland river short-distances vessels. The results are in line with reality, which verifies the scientificity and validity of the proposed model.

Keywords: green ship; clean energy technology; rough set; TOPSIS; selection; decision-making

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1. Introduction

With the development of the global trade and shipping industry, global shipping fuel consumption is increasing year by year. Fuel consumption is closely related to the emission of greenhouse gases and pollutants. It is estimated that greenhouse gas emissions from shipping fuel consumption account for about 3% of global CO_2 emissions [1], while CO_2 from ship exhaust emissions accounts for about 2% of global emissions [2]. We can see that ship emissions are major sources of pollution in the shipping industry. In recent years, relevant organizations such as the International Maritime Organization (IMO) have issued a series of regulations and measures to deal with navigation pollution caused by ships. In April 2018, the 72nd session of the Marine Environmental Protection Committee (MEPC) adopted "the initial IMO strategy on the reduction of greenhouse gas emission from Ships", which, for the first time, proposed a reduction target for the global shipping industry: the carbon emissions of the fleet by at least 40% by 2030 and 50% by 2050 compared to 2008, and will gradually move towards a zero-carbon goal. It has been found that decarbonization has been the future development direction of the shipping industry [3].

In the process of the decarbonization of shipping, academia and industry have started to focus on measures to reduce ship pollution from the aspects of speed control, hull design, and the application of emission reduction technologies [4]. Among many initiatives, the application of clean energy technologies is considered a key factor affecting the decarbonization of shipping [5–7]. Clean energy includes renewable energy that produces no or very little pollutants, such as wind energy, solar energy, biomass energy, hydro energy, geothermal energy, hydrogen energy, ocean energy, etc., as well as the use of low-emission fossil energy (e.g., LNG, LPG) and nuclear energy, etc. [8]. The ship's clean energy technology refers to the application of one or more forms of clean energy in the ship power system to improve the level of energy conservation and reduce the emission of ships as well as improve the working environment of vessels. According to the type of energy, the green ship clean energy technology mainly includes LNG fuel technology, battery power technology, solar energy technology, hydrogen fuel technology, ammonia fuel technology, wind energy technology, nuclear energy technology, etc. [9–11].

With the continuous breakthrough of clean energy technology and the continuous expansion of application scenarios, the application of clean energy technologies on ships is becoming more and more complicated because the potential clean energy technologies types are increasing, and the differences in the types of clean energy in terms of technical, economic and environmental criteria, which makes the selection of clean energy technologies for ships more difficult [6]. Under the double pressure of tightening environmental protection policies and ship renewal, how to choose the suitable clean energy technology for different ships is an urgent problem to be solved in the shipping industry.

In terms of the decarbonization path of the shipping industry, the direction of the technical means of improvements in ship energy efficiency and the transition to clean alternative energy has been determined. Although all parties have basically reached an agreement on the direction of emission reduction, the viewpoints of each subject in the implementation path of international shipping emission reduction are different or even have a large difference, which determines that the path to net-zero emissions in the shipping industry will be full of uncertainties. Some scholars have started to pay attention to the decision-making of technology selection for emission reduction in the shipping industry under uncertain information, mainly focusing on the aspect of low-sulfur control technology, the alternative fuels selection, energy efficiency improvement, etc.

Qualitative evaluations based on the literature and industry experience are commonly used methods of analysis. Martin Viktorelius [12] used the literature analysis method to discuss the application of energy-powered technologies in ships and determined how the technology is implemented by analyzing the relationship between technology, organization, and energy efficiency. DNV GL [13] conducted a qualitative comparison of alternative fuel technologies, including hydrogen, ammonia, methanol, LPG, hydrogenated vegetable oil (HVO), Li-ion batteries, and other alternative clean energy sources for ships, concluding that there are no clear-cut options for alternative marine energy for future shipping. Hui Xing et al. [14] summarized the potential alternative marine fuel options through a literature review. The relevant properties of zero-carbon or carbon-neutral fuels were analyzed, and the options of potential marine fuel options were ranked qualitatively.

In addition to this, some scholars have used quantitative evaluation methods to assess different emission reduction technologies, such as Jingzheng Ren, Marie Lützen, et al. [15] extracted nine indicators from four major aspects: technology, economy, sociopolitical and environment, and evaluated the sustainability of three low-sulfur abatement technologies (scrubber tower, low-sulfur fuel, and LNG) using AHP and VIKOR methods. The results showed that LNG technology had the best effect. However, only technical maturity indicators were considered in the technical attributes—the indicators were too single. Jingzheng Ren et al. [16] improved the indicator system in a subsequent study. In terms of technical attributes, in addition to technical maturity, this study also included reliability and energy storage efficiency. This paper further constructed a fuzzy hierarchical analysis (FAHP) and DS evidence theory selection decision model to evaluate alternative energy options for shipping and verified the validity of the model through case studies, but there is also the disadvantage that the index weight acquisition is too subjective. Bui, K.Q., and Olcer et al. [17] focused on the three major criteria (social, economic, and environmental) of the sustainable development of shipping by using AHP and TOPSIS methods to analyze and evaluate four alternatives (low-sulfur fuel, methanol, scrubber, and LNG) for low-sulfur emissions from ships and concluded that low-sulfur fuel was the best alternative under the current maritime regulations, followed by methanol, scrubbers, and LNG. AR Kim et al. [18] aimed to reduce sulfur emissions in the shipping industry by evaluating the response direction of Korean shipping companies to SO_x regulations, and taking three alternatives: switching to low-sulfur fuels, installing scrubbers, and the application of LNG-powered ships, it was found that the response direction differed for different ship ages and tonnages. Seddiek, I.S. and Elgohary [19], and Z.L. Yang [20], etc., took SO_x and NO_x reduction as the perspective and analyzed the technical strategies of ship emission reduction through the literature analysis method and AHP-TOPSIS method, respectively. Christian Haehl et al. [21] proposed a real option regime from the perspective of a regulatory uncertainty transformation model for determining the optimal investment and technology choice for ships by using two-stage modeling to characterize market demand and introducing environmental regulations as a stochastic component; the results demonstrate that regulatory uncertainty can influence investment patterns and decision-making in ship operation technology.

Bekir Sahin [22] used an improved Gaussian fuzzy analytic hierarchy process (IG-FAHP) to analyze and evaluate four alternatives for ship emission reduction (new ship design, energy efficiency technology, clean energy technology, and automation technology), it was found that Gaussian fuzzy numbers have advantages over triangular or trapezoidal fuzzy numbers, which verified the applicability of the model. Omer Berkehan Inal [23] used AHP hierarchical analysis to evaluate four fuel cell types in terms of eight criteria: safety, emissions, efficiency, cost, lifetime, power output, fuel type, and cell size to evaluate the options. Some scholars such as Gilbert [24], Maja Percic [25,26], and Ailong Fan [27], etc., have used the whole life cycle approach, taking different waters and ship types as objects, to develop the environmental and economic assessment of shipping fuels and power.

The above literature analysis shows that the research on the application of clean energy technologies from the decarbonization perspective has just started, and the comparative analysis and economic evaluation of clean energy technologies are mainly conducted from the qualitative perspective and the whole life cycle perspective. Most of the studies are still from the sulfur-emission reduction perspective, carrying out the comparative analysis of different shipping green technologies (such as installation of desulfurization tower, low-sulfur fuel, LNG technology, etc.).

In summary, it was found that the following shortcomings exist in the above research: (1) The study on the selection of clean energy technologies for ships is mainly carried out with the objective of the economy and environmental protection. There is a lack of research on the selection of clean energy technologies for ships of different tonnages and voyages under multiple criteria. (2) Bibliometrics, AHP, or group decision-making methods are mostly used in the evaluation models for the selection and decision-making of shipping emission reduction technologies, which have the problems of strong subjectivity and insufficient mining of sample data information.

Given the uncertain environment, the selection of clean energy technologies is often a process involving multiple criteria and evaluating multiple alternatives. To address this issue, this paper establishes a multi-dimensional decision support framework for clean energy technologies for the green ship industry to make supplementary decisions for shipowners. The main contributions of this paper are as follows: (1) Taking the decarbonization of the shipping industry as the perspective, we comprehensively analyze the application characteristics of different clean energy technologies, construct a multi-dimensional evaluation index system considering the technicalities, economy, environment, and safety, and take specific routes and ship types as examples to excavate the key indicators that affect the selection decision-making of clean energy technology. (2) To address the problems of strong subjectivity of the current shipping emission reduction technology selection evaluation model and inadequate information mining of the sample data by the model, the RS method, which does not require a priori information, is introduced and combined with the TOPSIS method to help shipowners and operators make decisions on the selection of clean energy technologies under uncertain information.

2. Clean Energy Technology Selection Method

The decision of clean energy technology selection for the green ship industry belongs to a typical multi-criteria decision-making (MCDM) problem, which mainly portrays the prioritization and ranks the alternatives according to multiple objectives in the shipowner's decision-making process [28]. The TOPSIS method can handle multi-constrained decision criteria. It is an effective method to solve the multi-program selection problem. However, the TOPSIS method is more subjective in constructing the standardized matrix, where the determination of weights is generally derived from expert experience. It is especially when new technologies are generated, and experts cannot accurately predict the relevant indicators of the technologies that rely on expert scores that will produce a particular bias.

Compared with subjective weight determination methods such as AHP, the RS method does not require a priori information—the solution process is driven by actual samples, which is highly operable. The RS method can approximate the training data, find the minimum set of attributes, and obtain effective decision rules. Thus, this paper establishes a RS-TOPSIS-based decision-making model to improve the accuracy and scientificity of a ship's clean energy technology selection decision. By analyzing the application solutions of clean energy technology in different ship types, it will make the transition of green ships to clean energy more accessible and reduce the risk of making the relevant ships become stranded assets, which can provide a reference and basis for shipowners to carry out the transition of green ships.

The decision framework of this study is shown in Figure 1. This paper combines RS theory with the TOPSIS method to evaluate clean energy technology alternatives. Firstly, the RS method is used to approximate the target attributes and calculate the weights of each target attribute; secondly, the TOPSIS method is used to standardize the constructed initial decision matrix, and the matrix is multiplied by the target attribute weight of the RS processing to obtain a positive, the negative ideal solution and their distances; finally, the relative closeness of different green ship clean energy technology alternatives are calculated and ranked to obtain the selection decision result of green ship clean energy.

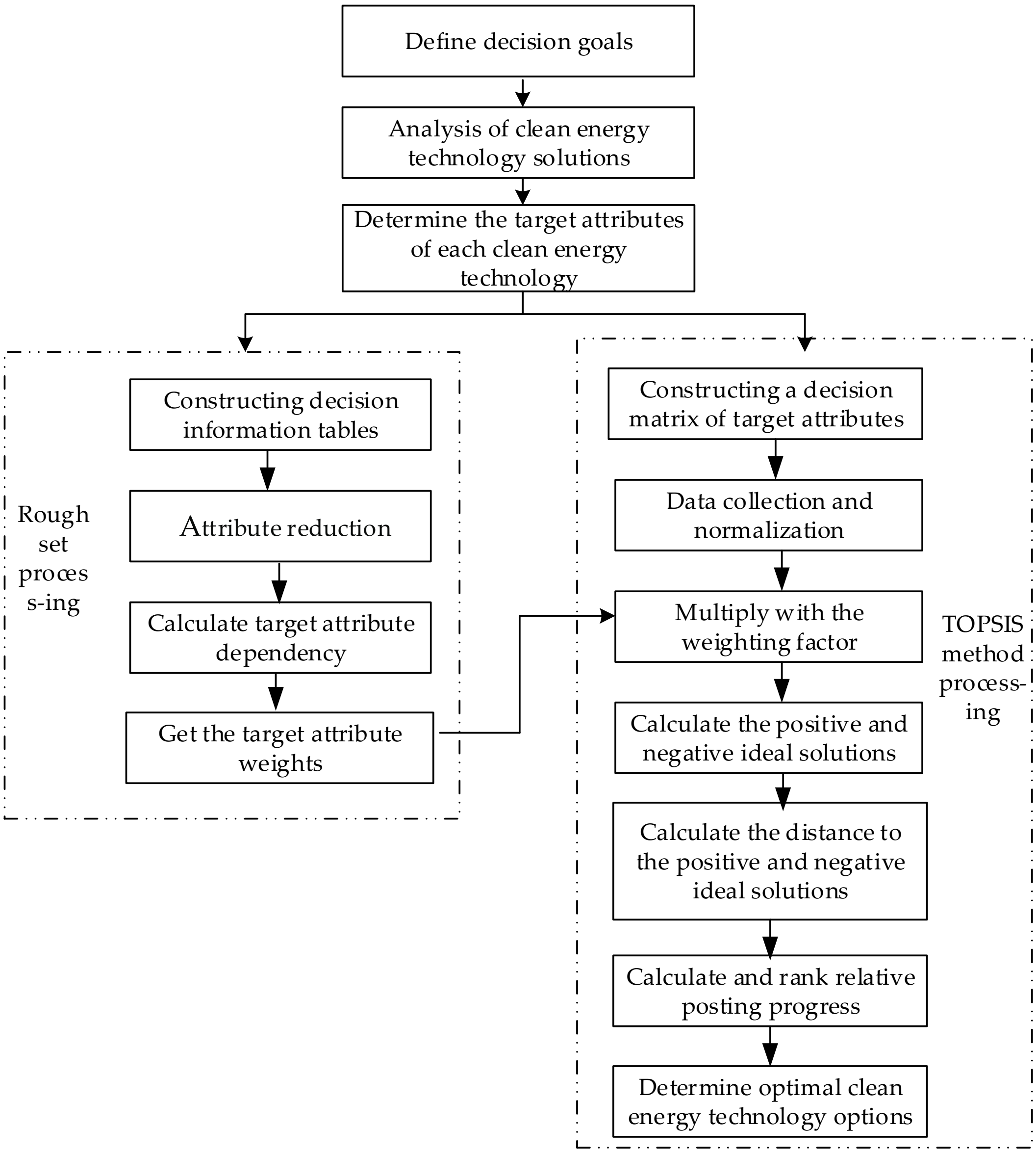


Figure 1. The selection process of clean energy technology for green ships.

2.1. Identification of Clean Energy Technology Alternatives

Through a literature review and analysis of research reports, it was found that the available clean energy technologies can be classified into the following types (see Table 1).

Table 1. Classification of clean energy technologies.

Technologies	Technology Classification	Technology Name
Clean Energy Technologies	Alternative Fuels Technologies	Low-carbon fuel technologies: LNG fuel, LPG fuel, dual-fuel, methanol, HVO, etc.
		Zero-carbon fuel technologies: hydrogen fuel, ammonia fuel, biofuel (bio-LNG, bio-methanol), etc.
	Electric Power Technologies	Pure battery power technology, fuel cell technology, supercapacitor, hybrid power
	Renewable Energy	Solar energy technology, wind-assisted propulsion technology, bioenergy technology, hydro energy technology, wave energy technology
	Nuclear Energy Technology	Nuclear propulsion technology

Among many clean energy technologies, nuclear power technology has obvious advantages, such as no-exhaust emissions, no need for frequent fuel replenishment, high propulsion efficiency, etc. However, barriers such as low public acceptance and low effectiveness limit its wide application in the shipping industry. Renewable energy technologies such as wind assist and solar propulsion can only be used as an auxiliary energy source for ships due to their low conversion rate and limited availability on ship types. In addition, the application of battery power technology in deep-sea shipping is limited due to low energy density and short-range. This paper offers a literature review combined with the results of multiple comparisons, such as the handheld orders for clean energy ships and the research and development of clean energy ships released by platforms such as Clarkson, DNV GL, ABS, etc. In addition, this paper mainly selects LNG fuel power, LPG fuel power, methanol (from fossil energy) fuel power, biofuel power (HVO), ammonia fuel cell, hydrogen fuel cell, and pure battery power technologies as samples noted as $U = \{T_1, T_2, T_3, T_4, T_5, T_6, T_7\}$. The proposed method will evaluate and analyze the seven clean energy technology alternatives for green ships.

2.2. Determination of Target Attributes of Clean Energy Technology Program

The choice of clean energy technology solutions in the green ship industry is affected by many factors. Acciaro et al. [29] and Rojon and Dieperink et al. [30] attribute it to organizational factors, shipowner behavior factors, market factors, etc. The International Renewable Energy Agency (IRENA) [31] has further sorted out these factors, and the organizational factors are attributed to the formulation of politics and related norms. The behavior of shipowners is mainly affected by economic factors, such as investment costs and operating costs. Market factors mainly include market incentives, benefits, etc. In addition, non-market factors mainly refer to the complexity of clean energy's own characteristics, such as technological uncertainty and security.

At present, various clean energy technologies show great differences in terms of economy, technology maturity, technology adaptability, emission reduction effect, safety, etc. For example, LNG fuel performs well in terms of technology maturity and economy, but the carbon emission reduction effect is average. Hydrogen fuel and ammonia fuel perform better in emission reduction effects, but the economy and safety are relatively poor and technically immature. The technology of pure electric ships has matured, but the limitation of volumetric energy density leads to the limitation of its application in long-distance and large-tonnage ships. At the same time, the chemical properties of each clean energy are different, resulting in different environmental hazards in the event of leakage. For example, ammonia fuel has higher toxicity and is less harmful to the environment. HVO fuel has lower toxicity and is less harmful to the environment. These influencing factors can be further categorized as technical, safety, economic, political, social, and environmental factors.

The selection of clean energy technologies for green ships is a complex and comprehensive issue. Decision-makers usually face several conflicting criteria when selecting the most sustainable clean energy technology with the best overall benefits. Currently, economic, technical, environmental, social, and political standards are mainly used to select emission reduction technologies for shipping [15–17]. These criteria correspond to the influencing factors in the previous section. Under each standard, there are the corresponding sub-criteria. For example, technical maturity and technology application readiness are technical criteria. Energy costs and engine retrofit costs are economic criteria, and CO_2 emissions, NO_x emissions, etc., are environment-based criteria. According to the findings of previous studies, technological, environmental, and economic standards are the critical criteria that influence the choice of a particular alternative clean energy source [14]. Andersson et al. [32] also obtained similar findings in their study: when the clean energy technology path is unclear, policy support has little impact on the technology decision-making process.

In this paper, considering that in the early stages of clean energy technology development, the degree of policy support is often influenced by emission reduction effect, technology maturity, safety, and other indicators. At present, there is no clear direction for countries to support different clean energy policies for ships. Based on this, this paper does not consider the influence of policy factors but only the characteristics of the technology itself to make a decision on the selection of clean energy technologies. According to the analysis results of different influencing factors and the characteristics of each clean energy technology, the four dimensions of economic, technical, environmental, and safety are evaluated comprehensively. The corresponding secondary index system is constructed (see Table 2).

Table 2. Green ship clean energy technology selection index.

Guideline Level	Indicator Level	Definition
Economic	Investment Cost (C_1) [15,16]	The cost of retrofitting and new construction of clean energy propulsion systems and supporting infrastructure increases or decreases compared to fuel oil ships
	Energy Cost (C_2) [15,16]	The degree of increase or decrease in the fuel cost of clean energy ships compared to fuel oil ships
Technical	Volumetric Energy density (C_3) [13,14]	The energy contained in a unit volume, the higher the value, the smaller the required fuel tank volume, and the better the ship's endurance
	Technical Maturity (C_4) [13,14]	The maturity level of energy application technologies and power systems
	Energy Availability (C_5) [13,14]	The shipping industry belongs to the downstream end-use of the energy industry chain and depends on the supply capacity of the upstream energy industry
	Technical Application Readiness (C_6) [13,14]	Specific requirements of the technology application, such as the difficulty of the technology in terms of vessel type, supporting infrastructure layout, and considering the maturity and availability of the technology and energy
Environment	Effect on CO_2 Reduction (C_7) [15,16]	Reduction of CO_2 emissions after fuel oil substitution
	Effect on NO_x Reduction (C_8) [15,16]	Reduction of NO_x emissions after fuel oil substitution
	Effect on SO_x Reduction (C_9) [15,16]	Reduction of SO_x emissions after fuel oil substitution
	Effect on PM Reduction (C_{10}) [15,16]	Reduction of PM missions after fuel oil substitution
Safety	Probability of Risk Occurrence (C_{11}) [14]	In the process of energy filling, storage, and supply, the probability of energy leakage depends on the characteristics of fuel, such as auto-ignition point and flashpoint. In this paper, the flammability and explosiveness of fuel represent the probability of risk occurrence.
	The severity of Consequences (C_{12}) [14]	In the event of energy leakage, the harm to the environment and the human body is characterized by the fuel toxicity in this paper.

Different clean energy technologies have different indicator performance. In order to explore the path of clean energy technology development, different maritime agencies such as DNVGL, ABS, IRENA, etc., have carried out studies on the performance of each clean energy technology to help shipowners understand the direction of clean energy technology development in the shipping industry. Considering that the application of clean energy technologies is in its early stages, the performance of many indicators lacks real-ship verification and is more dependent on expert experience. The performances of the indicators are all analyzed qualitatively, such as the reports [6,13] on maritime fuels issued by DNVGL institutions are all based on the 1–5 quantitative scoring method, and the relevant data are obtained through expert questionnaire research from shipyards, universities, shipping authorities, etc. Through the comparative data analysis of reports and papers of multiple institutions, it was found that the scores of each sample data were consistent. There is not much difference in the implementation progress of each clean energy technology in each country at present. Therefore, this paper uses the above sample information to carry out research.

According to the relevant reports published by DNVGL [6,13], the qualitative analysis results of various clean energy technology attributes by Ampah [33], combined with the analysis of different clean energy technology attributes by ABS institutions [34,35], the critical attribute performances of each clean energy technology were obtained as shown in Table 3. Among them, the investment cost, energy cost, and technical application readiness of electric ships have different performances in different waters, different voyages, and different ship types [25–27]. These three indicators are used as variables.

Table 3. Performance of target attributes of different clean energy technologies.

Criteria	LNG Powered (T_1)	LPG Powered (T_2)	Methanol Powered (T_3)	HVO Powered (T_4)	Ammonia Fuel Cell (T_5)	Hydrogen Fuel Cell (T_6)	Pure Battery Powered (T_7)
Investment Cost (C_1)	4	4	4	5	3	1	V [a]
Energy Cost (C_2)	5	5	3	2	1	1	V [a]
Volumetric Energy Density (C_3)	4	4	4	5	3	2	1
Technical Maturity (C_4)	5	4	3	5	2	1	3
Energy Availability (C_5)	4	4	3	1	2	1	2
Technical Application Readiness (C_6)	5	3	4	3	2	1	V
Effect on CO_2 Reduction (C_7)	1	1	1	3	5	5	5
Effect on NO_x Reduction (C_8)	5	1	3	1	5	5	5
Effect on SO_x Reduction (C_9)	5	5	5	4	5	5	5
Effect on PM Reduction (C_{10})	5	5	5	3	5	5	5
Probability of Risk Occurrence (C_{11})	1	2	4	5	2	1	5
Severity of Consequences (C_{12})	5	5	3	5	1	5	5

Note: 1–5 indicates the status level, 1 is very poor and 5 is excellent. V: Varies, not applicable for deep-sea shipping. [a] Needs to be evaluated case by case, with large regional variations.

2.3. RS Method to Determine Attribute Weights

The concept of RS was introduced by the Polish mathematician Pawlak [36] in 1982, and is one of the most important tools in soft computing, which is currently studied in applications in medical diagnosis [37], machine learning [38], pattern recognition [39], and data mining [40]. RS has advantages in dealing with decision systems with uncertain and incomplete information, with strong real-time, and is easily operable. In this paper, we adopted RS theory to establish the attribute sets and constructed a decision system of clean energy technology for green ships. Furthermore, this method can carry out attribute reduction based on data discretization results, and calculate the weights of each attribute [41]. The specific process is as follows:

Step 1. Construct the information table for decision-making of clean energy technology options. Set $S = \{U, C, F, d\}$ as the knowledge expression system of clean energy technology options for green ships, where, $U = \{T_1, T_2, T_3, \cdots, T_i\}$ is the set of options, and the constituent element $T_i (i \le n)$ in U is called the evaluation object. $C = \{C_1, C_2, C_3, \cdots, C_i\}$ represents the set of all necessary clean energy attributes, the associated element $C_i (i \le m)$ in C represents the corresponding attribute. F is the attribute value. d is the information function.

For any $C_i \subseteq C$, if $ind(C_i) = ind(C)$ and C_i is independent, then C_i is a simplification of C, denoted as $red(C_i)$.

$$ind(C)=\{(x, y) \in U \times U \,|\, \forall c \in C, c(x) = c(y)\} \quad (1)$$

The relation $ind(C)$ forms a classification of U, denoted by $U / ind(C)$.

Step 2. $S = \{U, C, F, d\}$ as a set of knowledge expression systems for clean energy technology solutions for $C_i \subseteq C$, $U / ind(C_i) = \{C_1, C_2, C_3, \cdots, C_i\}$, the amount of information of the knowledge C_i is as follows:

$$I(C_i) = \sum_{i=1}^{n} \frac{|C_i|}{|U|} \left| 1 - \frac{C_i}{U} \right| = 1 - \frac{\sum_{i=1}^{n} C_i^2}{|U|^2} \quad (2)$$

where, $|C_i|$ denotes the base of C, $\frac{C_i}{U}$ denotes the probability of occurrence of the equivalence relation C_i in U.

Step 3. Calculate the importance of the target attributes of each evaluation alternative as:

$$SGF_{C-C_i} = I_C - I_{C-C_i} \quad (3)$$

Step 4. Weight of the target attributes of each evaluation alternative can be calculated with the formula below:

$$w(C_i) = S_{C-C_i} \Big/ \sum_{i=1}^{n} S_{C-C_i} \quad (4)$$

Through the above process, the weight of each attribute of the green ship clean energy technology alternatives can be obtained.

2.4. TOPSIS Method to Determine Alternatives Ranking

The TOPSIS method is mainly used to solve multicriteria decision-making problems [42]. Multiple alternatives are ranked by detecting the distance between the optimal solution and the worst solution (i.e., positive and negative ideal reference points). If the evaluation alternatives are close to the optimal solution and the distance from the worst solution is the farthest, the alternative is the optimal alternative; otherwise, it is the worst. The specific steps are as follows.

Step 1. Construction of initial evaluation matrix.

Construct an initial evaluation matrix for different clean energy technology evaluation alternatives $X = (x_{ij})_{u \times v}$, where X_{ij} denotes the *v*th target attribute corresponding to the *u*th option $(i = 1, 2, 3, 4, \cdots, u; j = 1, 2, 3, 4, \cdots, v)$.

$$X = (x_{ij}) = \begin{bmatrix} x_{11} & \cdots & x_{1v} \\ \vdots & \ddots & \vdots \\ x_{u1} & \cdots & x_{uv} \end{bmatrix} \quad (5)$$

Step 2. Establish a standardized decision matrix.

Considering the different measurement units and scales, it is necessary to normalize the target attributes in the matrix X to make different variables comparable—that is, to determine the type of each target attribute in the matrix X. For the benefit criteria in clean energy technology, the larger the value is, the better it is—Equation (6) can be used to calculate this value:

$$y_{ij} = \frac{x_{ij} - \min_j x_{ij}}{\max_j x_{ij} - \min_j x_{ij}} \quad (6)$$

For cost attributes, the smaller the attribute value, the better, and it is normalized according to Formula (7):

$$y_{ij} = \frac{\max_j x_{ij} - x_{ij}}{\max_j x_{ij} - \min_j x_{ij}} \quad (7)$$

Step 3. Establish a weighted standardized decision matrix.

The R matrix, after normalizing the matrix, X is further weighted by multiplying the values of each column in the normalized decision matrix R with the weights w_j calculated by the RS to obtain the following weighted normalized decision matrix Z:

$$Z = (z_{ij})_{mn} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix} = \left(w_j \times y_{ij}\right)_{mn} \quad (8)$$

where, $w_j \geq 0$, and $\sum_{i=1}^{n} w_j = 1$.

Step 4. Calculation of the degree of closeness of each evaluation alternative

Firstly, compute the positive Z^+ and negative ideal solutions Z^- of Z:

$$Z^+ = \left[\max\left(z_{ij}\right)\right] = \left[z_1^+, z_2^+, z_3^+, \cdots, z_n^+\right] \quad (9)$$

$$Z^- = \left[\min\left(z_{ij}\right)\right] = \left[z_1^-, z_2^-, z_3^-, \cdots, z_n^-\right] \quad (10)$$

Further calculate the distance between each evaluation alternative and the positive and negative ideal solutions R_{i+} and R_{i-}:

$$R_{i+} = \sqrt{\sum_{j=1}^{n} z_{ij} - z_{ij}^+}$$

$$R_{i-} = \sqrt{\sum_{j=1}^{n} z_{ij} - z_{ij}^-} \quad (11)$$

Finally, calculate the relative closeness coefficients σ_i^+ of the evaluation programs to the positive ideal solution:

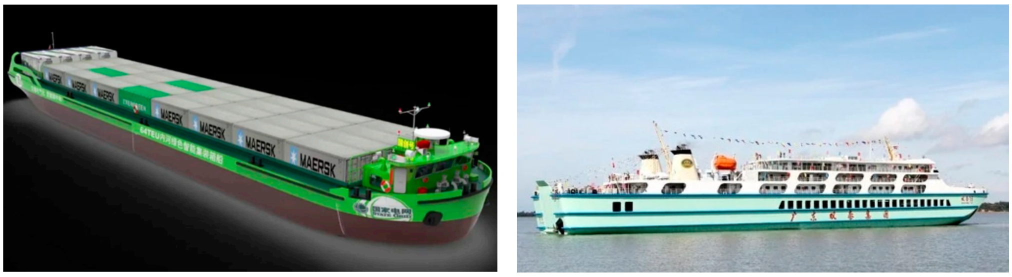
$$\sigma_i^+ = R_{i-} / (R_{i+} + R_{i-}) \qquad 0 \leq \sigma_i^+ \leq 1 \quad (12)$$

The closeness coefficients σ_i^+ reflect the degree to which the clean energy technology decision-making program is close to the positive ideal solution, and the larger the value, the better. The relative closeness coefficient of the general evaluation alternatives is between 0 and 1. Clean energy technology options can be sorted according to the closeness coefficients.

3. Case Studies

3.1. Data Collection

To carry out the study, two different types of ships, namely, small inland river ships and large coastal ro-ro passenger ships, respectively, were selected as case studies where the vessels navigating in the inland waterways are relatively small, with an average tonnage of about 800 t. The selected inland river ship is a 64 TEU container ship in the Yangtze River system with a route of 250 km at a time from Zhejiang to Shanghai, this type of vessel has been completed as an electric demonstration vessel in China (Figure 2a). The coastal ship is a Qiongzhou Strait ro-ro passenger ship (Figure 2b). At present, the Qiongzhou Strait ro-ro passenger ship route has formed a ferry route with Xuwen port as the main port on the north shore and a ferry route connecting Haikou New Seaport and Xiuying Port on the south shore, where the distance between Haikou New Seaport and Xuwen Port is only 12 nautical miles, and the average tonnage of ships is 10,275 t. With the opportunity to build a clean energy island in Hainan, the Qiongzhou Strait is also actively promoting the application of clean energy for ro-ro passenger vessels. Table 4 shows details the parameters of the two case study vessels.



(**a**) (**b**)

Figure 2. Selected ships. (**a**) 64TEU container ship in the Yangtze River; (**b**) Qiongzhou Strait ro-ro passenger ship.

Table 4. Two case study ship parameters.

Ship Type Parameters	Length (m)	Breadth (m)	Depth (m)	Tonnage (t)	Design Speed (km/h)	Distance (km)
Inland River Ship (type 1)	71.4	12.6	3.3	1165	14.8	250
Coastal Ship (type 2)	119.88	20.3	6	8965	13.8	33

The literature [25–27] uses the whole life cycle method to make an economic analysis of different ship types; this paper draws on the calculation process and results of the literature and compares it with the economic performance of each clean energy obtained in Table 3, the evaluation data of investment cost and energy cost can be obtained, which is shown in Table 5. Using the proposed evaluation method of green ship clean energy in this study, the application of different clean energy technologies on different ship types is evaluated.

Table 5. Evaluation data of different clean energy technologies for two types of ships.

Criteria	T_1	T_2	T_3	T_4	T_5	T_6	T_7
Investment Cost (C_1)	4	4	4	5	3	1	5 (3) *
Energy Cost (C_2)	5	5	3	2	1	1	5 (3)
Volume Energy Density (C_3)	4	4	4	5	3	2	1
Technical Maturity (C_4)	5	4	3	5	2	1	3
Energy Availability (C_5)	4	4	3	1	2	1	2
Technical Application Readiness (C_6)	5	3	4	3	2	1	5 (3)
Effect on CO_2 Reduction (C_7)	1	1	1	3	5	5	5
Effect on NO_x Reduction (C_8)	5	1	3	1	5	5	5
Effect on SO_x Reduction (C_9)	5	5	5	4	5	5	5
Effect on PM Reduction (C_{10})	5	5	5	3	5	5	5
Probability of Risk Occurrence (C_{11})	1	2	4	5	2	1	5
Severity of Consequences (C_{12})	5	5	3	5	1	5	5

Note: * The data in () represents the index performance of coastal ro-ro passenger ships.

3.2. Clean Energy Technology Choice Decision Results

3.2.1. Weight Calculation

Combined with RS theory, the target attributes of clean energy for ship type 1 can be obtained as follows:

$$U / ind(C) = \{1,2,3,4,5,6,7\}$$
$$U / ind(C_1) = \{(1,2,3),(4,7),5,6\}$$
$$U / ind(C_2) = \{(1,2,7),3,4,(5,6)\}$$
$$U / ind(C_3) = \{(1,2,3),4,5,6,7\}$$
$$U / ind(C_4) = \{(1,4),2,(3,7),5,6\}$$
$$U / ind(C_5) = \{(1,2),3,(4,6),(5,7)\}$$
$$U / ind(C_6) = \{(1,7),(2,4),5,6,7\}$$
$$U / ind(C_7) = \{(1,2,3),4,(5,6,7)\}$$
$$U / ind(C_8) = \{(1,2,3,4),(5,6),7)\}$$
$$U / ind(C_9) = \{(1,2,3,5,6,7),4\}$$
$$U / ind(C_{10}) = \{(1,2,3,5,6,7),4\}$$
$$U / ind(C_{11}) = \{(1,6),(2,5),3,(4,7)\}$$
$$U / ind(C_{12}) = \{(1,2,4,6,7),3,5\}$$

Combined with Formula (1), the relationship between the target attributes of clean energy of ship type 1 is further obtained as follows:

$$U / ind(C - C_1) \neq U / ind(C)$$
$$U / ind(C - C_2) \neq U / ind(C)$$
$$U / ind(C - C_3) \neq U / ind(C)$$
$$U / ind(C - C_4) \neq U / ind(C)$$
$$U / ind(C - C_5) \neq U / ind(C)$$
$$U / ind(C - C_6) \neq U / ind(C)$$
$$U / ind(C - C_7) \neq U / ind(C)$$
$$U / ind(C - C_8) \neq U / ind(C)$$
$$U / ind(C - C_9) = U / ind(C)$$
$$U / ind(C - C_{10}) = U / ind(C)$$
$$U / ind(C - C_{11}) \neq U / ind(C)$$
$$U / ind(C - C_{12}) \neq U / ind(C)$$

According to the calculation results of the relationship between the target attributes, we can see that the two indicators of the C_9 "Effect on SO_x reduction" and C_{10} "Effect on PM reduction" are the reduced attributes in the decision system. It indicates that these two indicators will not impact the outcome of the choice of clean energy at this stage. Through further analysis of the two indicators, we can see that the performance of each clean energy technology in terms of "Effect on SO_x reduction" and "Effect on PM reduction" is relatively good from Table 5. The performance of each clean energy source on both indicators meets the requirements of long-term environmental regulation. Therefore, these two indicators are reasonable as reduced indicators.

Furthermore, according to Formula (2), the importance of the indicators is calculated by using the knowledge information in the RS as follows:

$SGF_{C_i} == \frac{\sum_{i=1}^{m}|C_i||U-C_i|}{|U||U-1|} = \frac{3\times4+2\times5+6+6}{7\times6} = 0.81$; and the importance of the other indicators can be obtained in the same way: $SGF_{C_2}=0.81$; $SGF_{C_3}=0.86$; $SGF_{C_4}=0.90$; $SGF_{C_5}=0.86$; $SGF_{C_6}=0.90$; $SGF_{C_7}=0.71$; $SGF_{C_8}=0.67$; $SGF_{C11}=0.86$; $SGF_{C12}=0.52$.

According to the formula $w(C_i)=S_{C-C_i}\Big/\sum_{i=1}^{n}S_{C-C_i}$, the attribute values of each index are calculated as follows:

$w(C_1)=w(C_2)=0.81/7.90=0.102$; $w(C_3)=w(C_5)=w(C_{11})=0.86/8.00=0.108$; $w(C_4)=w(C_6)=0.114$; $w(C_7)=0.090$; $w(C_8)=0.084$; $w(C_{12})=0.066$.

In the same way, the indicator weights of each clean energy alternative of ship type 2 can be obtained. The indicator weights' results of each clean energy alternative of ship type 1 and ship type 2 are shown in Table 6.

Table 6. Importance and weight of each target attribute of ship type 1 and ship type 2.

Ship Type	Attributes	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_{11}	C_{12}
Type 1	Importance	0.81	0.81	0.86	0.90	0.86	0.90	0.71	0.67	0.86	0.52
	Weights	0.102	0.102	0.108	0.114	0.108	0.114	0.090	0.084	0.108	0.066
Type 2	Importance	0.81	0.86	0.86	0.90	0.86	0.86	0.71	0.67	0.86	0.52
	Weights	0.102	0.108	0.108	0.114	0.108	0.108	0.090	0.084	0.108	0.066

It can be revealed in Table 7 that the indicators of C_4 and C_6 have the largest weights; that is, the technical maturity and technical application readiness indicators are the most critical indicators for the selection of the ship type 1 solutions. Secondly, volumetric energy density, energy availability, and probability of risk occurrence are also critical indicators determining if the clean energy technology option of ship type 1 is selected. Investment cost, energy cost, and effect on CO_2 reduction ranked third in importance. When choosing a clean energy technology solution for ship type 2, C_4 technical maturity is a rigid indicator that affects if the alternative is selected, followed by energy cost, volumetric energy density, energy availability, application readiness, and probability of risk occurrence.

Table 7. Analysis of model evaluation results.

Ship Type	Ship Type 1 (Small Inland River Short-Distance Cargo Ship)				Ship Type 2 (Large Coastal Ro-Ro Passenger Ship)			
Programs	R^{i+}	R^{i-}	σ_i^+	sort	R^{i+}	R^{i-}	σ_i^+	sort
LNG Powered T_1	0.15	0.26	0.638	2	0.15	0.26	0.638	1
LPG Powered T_2	0.16	0.21	0.569	5	0.35	0.22	0.378	2
Methanol Powered T_3	0.14	0.20	0.584	4	0.44	0.19	0.308	5
HVO Powered T_4	0.15	0.24	0.612	3	0.45	0.24	0.347	3
Ammonia Fuel Cell T_5	0.21	0.15	0.427	6	0.42	0.15	0.267	7
Hydrogen Fuel Cell T_6	0.26	0.14	0.351	7	0.38	0.14	0.275	6
Pure Battery Powered T_7	0.13	0.26	0.664	1	0.45	0.21	0.317	4

From the ranking of the indicators of the two types of ships, we can see that although the values of the indicator weights are slightly different, the technical maturity, technical application readiness, energy cost, energy availability, and probability of risk occurrence are all key indicators for the two ship types to determine if the alternative solution is selected.

3.2.2. Ranking of Clean Energy Technology Alternatives

According to Formula (4), the initial evaluation matrix is constructed from the screening indicators in Table 7.

$$X = \begin{array}{c} \begin{matrix} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 & C_{11} & C_{12} \end{matrix} \\ \begin{bmatrix} 4 & 5 & 4 & 5 & 4 & 5 & 1 & 5 & 1 & 5 \\ 4 & 5 & 4 & 4 & 4 & 3 & 1 & 1 & 2 & 5 \\ 4 & 3 & 4 & 3 & 3 & 4 & 1 & 3 & 4 & 3 \\ 5 & 2 & 5 & 5 & 1 & 3 & 3 & 1 & 5 & 5 \\ 3 & 1 & 3 & 2 & 2 & 2 & 5 & 1 & 2 & 1 \\ 1 & 1 & 2 & 1 & 1 & 1 & 5 & 5 & 1 & 5 \\ 5 & 5 & 1 & 3 & 2 & 5 & 5 & 5 & 5 & 5 \end{bmatrix} \end{array}$$

According to Formula (1), the initial evaluation matrix X is constructed from the screening indicators and original data in Table 2. Since the indicators in this paper use quantitative scores, the attribute indicators in the evaluation matrix X are standardized according to formula (6). Find the normalized decision matrix R:

$$R = \begin{array}{c} \begin{matrix} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 & C_{11} & C_{12} \end{matrix} \\ \begin{bmatrix} 0.75 & 1.00 & 0.75 & 1.00 & 0.75 & 1.00 & 0.00 & 1.00 & 0.00 & 1.00 \\ 0.75 & 1.00 & 0.75 & 0.75 & 0.75 & 0.50 & 0.00 & 0.00 & 0.25 & 1.00 \\ 0.75 & 0.50 & 0.75 & 0.50 & 0.50 & 0.75 & 0.00 & 0.50 & 0.75 & 0.50 \\ 1.00 & 0.25 & 1.00 & 1.00 & 0.00 & 0.50 & 0.50 & 0.00 & 1.00 & 1.00 \\ 0.50 & 0.00 & 0.50 & 0.25 & 0.25 & 0.25 & 1.00 & 1.00 & 0.25 & 0.00 \\ 0.00 & 0.00 & 0.25 & 0.00 & 0.00 & 0.00 & 1.00 & 1.00 & 0.00 & 1.00 \\ 1.00 & 1.00 & 0.00 & 0.50 & 0.25 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \end{bmatrix} \end{array}$$

According to Formula (8), the standard matrix R is multiplied by the weight w processed by RS, and then the weighted standardized decision matrix Z is obtained:

$$Z = \begin{array}{c} \begin{matrix} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 & C_{11} & C_{12} \end{matrix} \\ \begin{bmatrix} 0.08 & 0.10 & 0.08 & 0.11 & 0.08 & 0.11 & 0.00 & 0.08 & 0.00 & 0.07 \\ 0.08 & 0.10 & 0.08 & 0.09 & 0.08 & 0.06 & 0.00 & 0.00 & 0.03 & 0.07 \\ 0.08 & 0.05 & 0.08 & 0.06 & 0.05 & 0.09 & 0.00 & 0.04 & 0.08 & 0.03 \\ 0.10 & 0.03 & 0.11 & 0.11 & 0.00 & 0.06 & 0.05 & 0.00 & 0.11 & 0.07 \\ 0.05 & 0.00 & 0.05 & 0.03 & 0.03 & 0.03 & 0.09 & 0.08 & 0.03 & 0.00 \\ 0.00 & 0.00 & 0.03 & 0.00 & 0.11 & 0.00 & 0.09 & 0.08 & 0.00 & 0.07 \\ 0.10 & 0.10 & 0.00 & 0.06 & 0.21 & 0.11 & 0.09 & 0.08 & 0.11 & 0.07 \end{bmatrix} \end{array}$$

According to Formulas (9) and (10), the positive and negative ideal solutions of each clean energy technology evaluation alternative of ship type 1 are calculated, respectively, as:

$$Z^{+} = \{0.10, 0.10, 0.11, 0.11, 0.08, 0.11, 0.09, 0.08, 0.11, 0.07\}$$

$$Z^{-} = \{0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00\}$$

Calculate the distances of the positive ideal R_{i+} and negative solutions R_{i-} corresponding to each alternative by Formula (11). According to Formula (12), the closeness coefficients σ_i^{+} of each alternative relative to Z^{+} can be obtained, and the alternatives can be sorted according to the order of closeness coefficients. Similarly, the clean energy evaluation alternatives of ship type 2 can be sorted. The model evaluation results are shown in Table 7.

According to the relative progress of each clean energy technology alternative solution, the radar chart of the clean energy technology alternatives scores of ship type 1 and ship type 2 can be obtained, as shown in Figure 3.

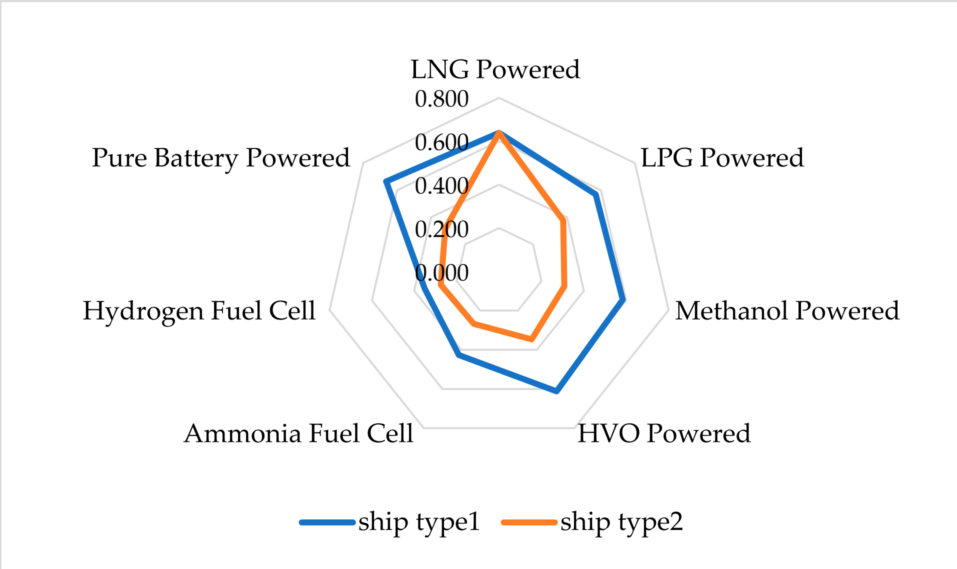


Figure 3. Radar chart of clean energy technology solutions for different ship types.

4. Discussion

As seen in Table 7 and Figure 3, pure battery-powered and LNG-powered technologies are the best clean energy technology solutions suitable for inland short-distance small cargo ships and coastal ro-ro passenger ships at this stage, respectively. The result is consistent with the statistics of the maritime sector (As shown in Figure 4, the data is as of December 2021). According to the Clarksons 2021 report, LNG-powered vessels account for nearly 30% of handheld order tonnage. By ship type, the most used LNG-powered technology is for tankers, followed by ferries, container ships, and offshore vessels. Although LNG fuel technology performs better in various index attributes for green vessels, and it is a clean energy technology that is currently used more in the field of green ships, it is clear from the performance of various indexes of LNG fuel technology that the technology is deficient in terms of emission reduction effect compared with other clean energy sources. With the strict implementation of decarbonization regulations, the LNG fuel technology will not have advantages.

The performance of emission reduction effect of pure battery power technology is relatively good, but its low volume energy density and short-range limit the application in large long-distance vessels, and it is currently more suitable for small vessels in close proximity such as small car/passenger ferries, offshore supply ships, and other active boats. Considering the different advantages of different clean energy technologies and so on. The development of a hybrid vessel by combining different fuels and power is a hotspot in green ship development at present.

In addition, from the performance of each clean energy technology attribute, we can see that in the trend of decarbonization of the shipping industry, with the continuous development and progress of clean energy technology, hydrogen fuel technology, and ammonia fuel technology, which have advantages in emission reduction effect, will be the key clean energy technologies in the future. From the results of the model runs, it is clear that this method can help shipowners to choose the most suitable clean energy technology alternative in an uncertain environment.

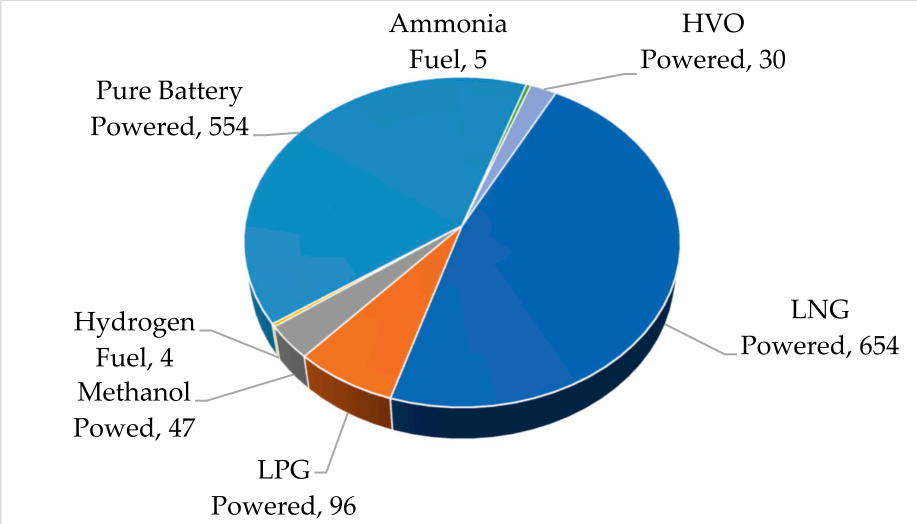


Figure 4. Green ships in hand and in operation. Data source: Based on data published on Clarkson's website and the DNV GL website.

5. Conclusions

In recent years, the process of environmental protection regulation in the shipping market has continued to accelerate, and the road to low-carbon and zero-carbon transformation is imminent. Ocean-going ships, coastal ships, and inland river ships are quite different in terms of voyage distance, ship size, and ship layout. Therefore, when choosing clean energy technology, the specific ship types in ocean, coastal and inland waters should be comprehensively considered from the perspectives of technical feasibility, energy availability, and economic, etc. and form a differentiated clean energy technology plan based on the size and range of the vessels. Through theoretical analysis and empirical research, the following main conclusions are drawn:

(1) Under uncertain conditions, this paper constructed a clean energy technology selection model and established a clean energy technology evaluation index system for green ships, containing 12 indicators in four dimensions, including economic, technical, environment, and safety. The key indicators that affect the selection of clean energy technology solutions are extracted from the two types of ro-ro passenger ships and short-distance small ships in inland rivers. The assessment results show that technical maturity, volumetric energy density, technical application readiness, energy cost, investment cost, effect on CO_2 reduction, and probability of risk occurrence are the key factors affecting the choice of clean energy technology options; the results are in line with reality. The paper provides a measure for the selection of clean energy technology solutions for different ship types in different waters.

(2) Seven clean energy technology alternatives such as LNG power, LPG power, methanol power, pure battery power, hydrogen fuel cell, ammonia fuel cell, and biofuel power are considered for different ship types. It is found that LNG power technology is the best solution for the decarbonization transition of large coastal ro-ro passenger ships at this stage, and pure battery power technology is the best clean energy technology for small short-distance inland river ships. The results obtained are in line with reality.

(3) The RS theory and TOPSIS method are combined to effectively determine the selection alternatives of clean energy technologies for green ships. This method converts the qualitative description of the applicability of existing clean energy technologies into a quantitative expression, which enhances the objectivity and scientificity of the evaluation results. The proposed method provides new insights in the field of clean energy technologies selection problems. Therefore, the proposed method is feasible

and can be used to select the best clean energy technology option from multiple alternatives under uncertainty.

In addition, this paper has the following shortcomings in the research:

(1) The application of clean energy technology for green ships is an emerging research field. Based on the limitation of data availability, the quantification of indicators in this paper has certain restrictions, and the current data comes from secondary information. Subsequently, with the expansion of the application scenario of green ship clean energy technology and the enrichment of relevant indicator data, it is intended to extract the relevant indicators and data of clean energy technology of different ship types in different waters, and apply them to the model to make the decision-making results more accurate.

(2) Furthermore, the research methods proposed in this paper will be extended and applied to more ship types and different waters. Meanwhile, other multi-criteria selection decision-making methods will be explored and compared with the model results of existing research.

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