# Decision support methods for sustainable ship energy systems: A state-of-the-art review

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## Abstract

The shipping sector has been under great pressure since the last decade to improve its environmental footprint, more so recently with the International Maritime Organisation target for a 50% reduction in greenhouse gas emissions by 2050, benchmarked to 2008 levels. These challenging goals have increased the interest towards alternative fuels and ship energy systems that can offer a more sustainable performance. The variety of potential technological solutions along with the multiple criteria employed to evaluate the ship energy systems with respect to sustainability considerations, renders the decision-making process for selecting ship energy systems challenging and highlights the need for dedicated decision support methods. This study presents a state-of-the-art review of the literature on decision support methods for enhancing the ship energy systems sustainability. The trends and gaps in the literature are identified, based on which, recommendations for future research are proposed. This study findings indicate that, among others, further research is needed to adapt more holistic approaches that include safety and reliability indicators as well as the social aspect of sustainability. This review can be beneficial for the maritime industry stakeholders, including policy makers, academics and ship owners/operators.

**Keywords:** decision support; state-of-the-art literature review; sustainability; ship energy systems;

## 1 Introduction

Shipping exhibits a great impact on the global emissions with a share of almost 3% of the global anthropogenic emissions in 2018, and is responsible for more than 1 million tonnes of Greenhouse Gas (GHG) emissions annually, resulting in a 9.6% increase of GHG emissions from international shipping compared to the 2012 levels [1]. It is estimated that the carbon emissions from shipping are larger than the total emissions of Germany, which constitutes the sixth-largest $CO_2$ emitting country in the world [2]. In addition, the fourth International Maritime Organisation (IMO) GHG study deduced that there was an 87% increase on the methane ($CH_4$) emissions between the period of 2012-2018, due to the extensive use of the LNG fuel, whereas the effect of the Tier II and III regulations led to lower rates of increase for the NOx emissions [1]. On the other hand, the same study reported that there is an increase on the SOx and PM emissions, despite the regulations for the sulphur reduction [1].

IMO has set strict regulations to reduce the exhaust gas emissions and to improve the ship energy efficiency. A stricter sulphur cap was imposed in 2020 aiming to decrease the sulphur global emissions to 0.5% with impact on approximately 70,000 ships [3]. In addition, the NOx Tier III regulation came into effect for the Baltic and the North Sea area in 2021. The Emission Control Areas (ECA) are also expected to be expanded in the future, with attention on the Mexican Caribbean and Mediterranean Seas as well as Japan [4]. Regulations such as the Energy Efficiency Design Index (EEDI), Energy Efficiency Operations Index (EEOI), the Ship Energy Efficiency Management Plan (SEEMP) and the Monitoring, Reporting and

Verification (MRV) are also expected to be reinforced in the future [5,6]. Finally, in 2018, a target was set to reduce the $CO_2$ emissions from the shipping sector by 70% until 2050 and the GHG emissions by 50% compared to the 2008 levels [2]. Therefore, the shipping industry has been facing great pressure to confine its environmental footprint and adopt a more sustainable performance.

Sustainability is a relatively new area of focus in the shipping industry [7–9]. As a result, there has not been great progress as in other modes of transportation [8]. Sustainability objectives in shipping operations such as economic, environmental, and energy efficiency cannot be achieved simultaneously, due to their conflicting nature [10]. In addition, there are various stakeholders setting contradicting goals, time terms and key performance indicators to assess those goals [7].

In the past few years, there has been a growing interest to enhance the sustainability of shipping operations due to their significant economic and environmental impact. Ship energy systems exhibit the most significant impact on the energy consumption and emissions, as well as the operational cost during the ship lifetime. Therefore, interest has been placed to the development of technologies, as well as investigation of alternative fuels and configurations aiming to improve the environmental and economic performance of the ship energy systems.

An overview on alternative energy efficiency methods that are applicable for ship energy systems was presented in [11]. Alternative options and applications of waste heat recovery for ocean-going ships are reported in [12–15], whereas the main technologies employed in shipping with focus on their waste heat recovery potential are presented in [4]. The overview of hybrid renewable energy system on ships was also investigated in [16,17]. In addition, potential alternative sustainable marine fuels were reviewed in [18], whereas the case of biodiesel is analysed in [19]. Focus has also been placed on the emissions reduction alternatives [4, 20–22] and the benefits of alternative marine fuels were identified. In addition, the possibility of employing fuel cell systems in maritime applications to reduce the ship emissions was reviewed in [23]. Finally, an overview of the possible carbon emissions reduction alternatives to identify the most promising solutions and quantify their mitigation potential was presented in [24,25]. Based on the preceding discussion, it is evident that there is a great number of established and emerging technologies, alternative fuels and possible combinations that renders the decision-making process for designing the ship energy systems challenging.

According to [26], 'Decision-making is the cognitive process leading to the selection of a course of actions among alternatives'. It constitutes a complex task and the greatest problem is how to assess the various alternatives with respect to the considered criteria [27]. Therefore, decision support models are often used to aid the decision maker during the system design phase. The large number of parameters related in each decision leads, in many cases, to the requirement of computerised decision support tools [26]. Decision making in the energy sector in general is a challenging process that is based on the consideration of multiple criteria. Especially when optimal sustainable energy systems are investigated, objectives that reflect different aspects of sustainability should be evaluated [28]. According to [29], 'the concern of sustainable provision of energy satisfying the present needs without compromising the ability of future generations to meet their needs is inescapable in the development of decision support models in the energy sector'.

Several studies presented an overview of methods that support decisions in shipping. Special focus has been placed on the overview of supporting decisions regarding solid waste management [30] or ballast water treatment methods [31], as well as on techniques regarding safety of the maritime operations [32,33]. In addition, the review of practises for weather routing or ship speed and voyage optimisation has attracted great attention [34–36].

Furthermore, several attempts are reported in the pertinent literature to the available methods and tools for supporting decisions in shipping with consideration of some aspect of sustainability. Ref. [10] reports a systematic literature review focused on multi-objective decision support methods to improve the environmental aspect of the shipping sustanability, which indicated that multi-objective optimisation methods will play a significant role in the decision making process. Similarly, recent studies [37,38] focused on optimisation methods for ship energy systems, highlighted the importance of the optimisation methods, as well as the need for further research in the area.

From the preceding analysis, it is evident that there has been a conciderable level of activity and interest from both academia and industry regarding the ship energy systems sustainability, with various attempts to develop and review technologies and methods that will facilitate the decision support for more sustainable ship energy systems. However, previous reviews have addressed fragmented parts of this area with focus on specific technologies and alternative fuels. Moreover, only few studies [10,37,38] focused on reviewing the methods/tools that can be employed for the decision support to enhance the ship energy systems sustainability and their main interest was the investigation of the optimisation methods.

Hence, this study aims to identify and analyse the range of decision support methods for sustainable ship energy systems, identify the research gaps and map the future directions in a structured review of the pertinent literature. It should be noted that 'energy systems' are defined as systems that transform energy from one form to another, 'primary energy to useful forms', such as mechanical, electric and thermal, according to [37]. For clarity, following this definition, this work focuses on the ship power generation systems and does not consider the analysis of power consumption, such as propeller or other end users or power distribution systems. In addition, due to the sustainability considerations in this work, components that are necessary for ships to comply with the emissions and energy efficiency regulations are also considered.

Therefore, this study addresses the identified knowledge gap by focusing on the extent of the decision support methods employed to improve the ship energy systems sustainability. This review is the first work to evaluate a wider range of the scientific area, extending the previous reviews and providing an overview of the state-of-the-art decision support methods for the ship energy systems sustainability, whilst covering the various methods, criteria and energy systems considered. This analysis is beneficial for all maritime stakeholders including ship designers, policy makers, academics and ship owners/operators. For the ship owner/operators and designers, this study is beneficial for identifying suitable methods for improving the sustainability of the next generation ships. On the other hand, the identified gaps in the literature provide a reference for the academics for future research. Finally, the technological trends and challenges inferred from the literature could provide a reference point for the future policies.

The remainder of this study is organised as follows. The research approach followed for the structured review is discussed in Section 2. The overview of the decision support methods for more sustainable ship energy systems as well as the main characteristics of the identified studies are provided in Section 3. The main findings from the performed literature review along with the identified gaps and trends are presented in Section 4. Finally, Section 5 summarises the main findings and provides recommendations for future research directions.

## 2 Research approach

The structure of this review was guided by the 12 steps recommended in [39]. First, the need for this review was established through an initial analysis of the literature in the field, where the significance of this review was identified, as well as the gap of similar studies was recognised. The scope of this literature review was established as to provide an overview and critically apraise the research progress on decision support methods for ship energy systems sustainability, thus leading to the following research question:

*What are the key features of ship energy systems decision support with sustainability considerations and a particular focus on criteria and methods adopted, as well as ship energy systems included?*

The Scopus database was employed for this review, as it consists the journal database with the largest peer-reviewed collection of articles in the field of engineering [40]. In the analysis only peer-reviewed articles published in English language were considered, whereas conference papers were excluded.

The set of keywords used including the title, abstract and body of articles was derived from the research question. The search terms belong to the four groups presented in Figure 1. In addition, references that were cited on the identified articles were also analysed as a secondary source [40].

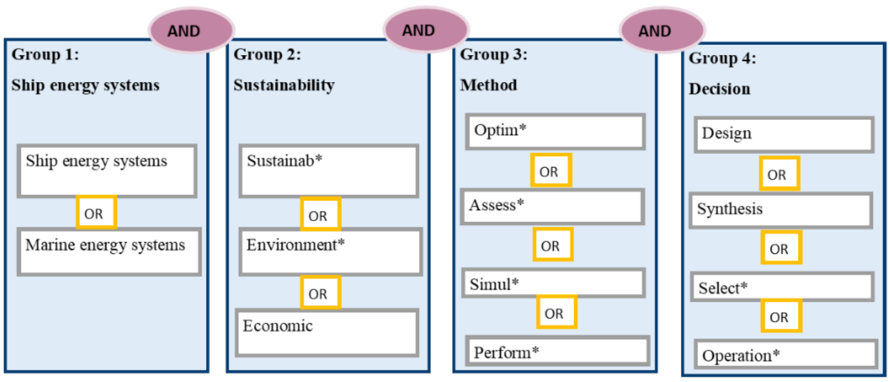


Figure 1. Keywords used in the literature review

Consequently, this iterative process led to more specific articles. According to [41], the advantage of this ‘snowball’ technique is that through the process key authors in the area were identified. Accordingly, a saturation level was reached to the point that there were no further arcticles identified. Finally, 95 articles were ultimately considered in this analysis. As a result, the state-of-the-art work on the field was recognised and critically reviewed as presented in the following section.

## 3 Decision support for sustainable ship energy systems

The results from the performed literature review are presented and discussed in this section. The yearly distribution of the reviewed articles is shown in Figure 2, showcasing the rising interest on the topic. This figure indicates that the number of articles published with relevance to the investigated topic has increased over time exhibiting a peek in 2018. The different methods employed for supporting decisions to improve the ship energy systems sustainability are identified, analysed and then discussed in the following sections.

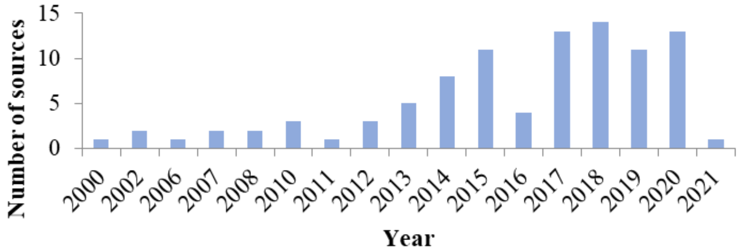


Figure 2. Distribution of articles

### *3.1 Life cycle assessment methods*

Life Cycle Assessment (LCA) is an environmental management tool employed to quantify the life cycle environmental impact of a product or process [42] and has been extensively used in the literature for decision support [43]. It has been widely applied to assess the environmental impact of transportation and some studies specifically adopted LCA in the shipping sector. An environmental accounting and reporting for marine transportation based on LCA was performed in [44]. An LCA software to estimate the environmental impact of ships holistically was developed in [45–48], with other studies focusing only on the gas emissions from ships [49–53].

Special attention has been given on the ship energy systems. An LCA for fuel cells comparing them with traditional diesel generators was performed in [54]. The environmental footprint of a traditional diesel-mechanical and an innovative battery-powered ship was evaluated with an LCA approach in [55], indicating that the use of batteries is not always the optimal solution. Another comparative LCA was presented in [56], identifying ship power plant configurations consisting of hydrogen operated fuel cells and batteries as the most environmentally promising alternative compared to diesel or hybrid systems. However, LCA studies are case-specific and therefore, they fail to capture general trends. In this respect, the typical LCA was complemented with a parametric trend analysis for scrubber systems in [57].

The preceding studies focused on the environmental aspect of sustainability only, whereas other aspects of sustainability have also been addressed in the pertinent literature. A systematic evaluation approach was introduced to support the policy makers with the selection of carbon emission reduction technologies by employing LCA and Life Cycle Costing (LCC) [58]. LCC was also employed in [59] and used to compare the alternatives by estimating the cost per environmental improvement against a benchmarked technology. Other studies combined LCA with either the required freight rate [60] or the material financial impact. Furthermore, a method was presented in [61–64] to support decisions on the environmental and economic sustainability of ships propulsion system by combining LCA and LCC. In addition, a life cycle performance assessment method was introduced in [65], where the LCC and LCA are incorporated in one indicator through normalisation, thus providing additional flexibility for including  other indicators of interest.

On the other hand, there are few studies reported in the pertinent literature that consider the social impact of marine technologies. A method to assess the three pillars of sustainability was presented in [9], but it was challenging to manage the trade-offs since each dimension was assessed separately.

Finally, marine fuels have also drawn interest  in terms of LCA [66–72]. In several studies, along with the environmental assessment of alternative marine fuels, the economic aspect was considered [73,74]. In [73], the safety of the alternative marine fuels was also evaluated, considering criteria such as the fuel density, auto-ignition temperature, flammability limits, stoichiometric air–fuel ratio, octane and cetane numbers. It should be noted that recent studies identified hydrogen as the most environmentally friendly alternative marine fuel, supporting the need to produce hydrogen by renewable energy sources [56,66,73,74]. Along the same lines, it is also critical for alternative fuels (e.g. natural gas) to be supported by a green supply chain [70].

### *3.2 Simulation and optimisation methods*

In this section, the existing literature for supporting decisions on ship energy systems with sustainability considerations by employing simulation or optimisation methods is discussed.

Table 1 enlists the identified studies that were focused on the decision support for sustainable ship energy systems; these studies are presented and discussed in the following paragraphs. The studies of Table 1 are clustered according to the employed method, considered systems and the assessment criteria, including environmental, economic, technical, safety, EEDI and energy efficiency related. It should be noted that in the category of environmental criteria, the methods that consider the gaseous emissions are included, whereas methods that estimate the energy or exergy efficiency of the ship energy system are clustered in the category of energy efficiency. The EEDI estimates the carbon emissions and simultaneously is employed as an indicator to improve energy efficiency; thus, it is accounted as a separate criterion to avoid double counting in both the environmental and energy efficiency categories.

Regarding the method categorisation, simulation is considered to denote models developed to predict or assess the investigated systems' performance for specific scenarios. On the other hand, optimisation tools identify the optimal system configuration, depending on the criteria selected. Optimisation tools usually require the use of a simulation model that estimates the systems performance, which is employed within the optimisation process. The level of the optimisation method, where relevant, is highlighted at the right column of Table 1. Three levels of optimisation focus are identified: synthesis, design and operation [75]. The synthesis optimisation includes the selection of the optimal components. The generation of a number of possible alternative systems configurations and the selection among them according to their performance analysis is part of the synthesis process [76]. The design of a given system is related to the technical characteristics and the sizing of the components, whereas operation of a given system expresses the operating specifications [75].

As it is evident from Table 1, a considerable number of studies focused on alternative solutions to reduce the gas emissions from ships. The economic impact and the potential of the SOx emissions reduction technologies are investigated in [77–79]. In addition, the economic and gaseous emissions reduction potential of black carbon technologies was assessed in [80], whereas the efficiency of the NOx and SOx emissions reduction technologies was investigated in [81]. Several studies also discussed the integrated performance of specific propulsion systems with emissions abatement technologies regarding economic criteria [82] or including the technologies emissions reduction potential [83] along with the energy reduction efficiency [84] and emissions control retrofitting cost [85].

Waste Heat Recovery (WHR) systems were also investigated as a means to improve the ship power plant efficiency and as a result, reduce the fuel energy consumption and the gaseous emissions. Several studies investigated the performance of a WHR system on a specific ship type considering different criteria [86–93]. Models were developed to simulate the performance of WHR from dual fuel engines operating at design and off-design conditions as reported in [94]. A variety of studies also discussed the design, or the optimal fluid selection of Organic Rankine Cycle (ORC) systems integrated with the ship power plant regarding various technical, economic and efficiency criteria. The optimal fluid selection of an ORC system with regards to energy efficiency and technical criteria was reported in [95,96]. The synthesis, design, and operation optimisation of an ORC system was presented in [97,98], whereas the ORC systems design optimisation was reported in [99,100]. The ORC system optimisation integrated with other ship energy systems was also discussed in [101–103].

Furthermore, innovative systems that lead to an improved ship energy efficiency and environmental impact were investigated. The simulation of a hybrid system that includes Solid Oxide Fuel Cells (SOFC) was presented in [104,105], whereas, a hybrid system including solar panels and battery was introduced and its potential to improve the ship efficiency and reduce the carbon emissions was discussed in [106].

The investigation of alternative propulsion systems and their integration with emissions reduction or WHR technologies considering different objectives was reported in [107–110], whereas alternative fuels for the propulsion system were compared and discussed in [111,112]. The design optimisation of the propulsion system was discussed in [113–115] taking into account different objectives. Furthermore, the design optimisation of more innovative propulsion systems (hybrid propulsion systems) was performed in [116–121].

Regarding the operational optimisation of the propulsion system, a variety of studies was presented focusing on complex ship power plants, including hybrid systems. The operation optimisation of a novel hybrid system with hydrogen production from a solid oxide electrolyser was introduced in [122], whereas the economic optimisation of an electric propulsion system operation was proposed in [123,124]. In addition, models for the load allocation optimisation were presented in [125,126].

Recently, all-electric ship power configurations are considered a promising alternative for reducing emissions and improving the ship energy efficiency [127]. However, one of the main challenges of these systems is the introduction of a suitable power management system, therefore, in the existing literature, several studies reviewed the methods for control and design of microgrids and power management on ships [128–132]. A method to optimise the power management of an all-electric ship with energy storage is proposed in [127,133], indicating that an optimal power management system positively impacts both the cost and carbon footprint of the ship. The operation of a hybrid system without energy storage is optimised in [134], concluding that meta-heuristic optimisation methods can be promising for power management optimisation, compared to the traditional techniques [132].

Furthermore, several studies employed optimisation techniques to support decisions for the synthesis of the ship propulsion system integrated with other ship energy systems considering both environmental and economic criteria [135,136], as well as safety criteria, such as availability and frequency of black-out [137].

In very few cases, the simultaneous optimisation of the synthesis, design or operation of the ship energy systems was addressed. The synthesis and design optimisation of the integrated ship systems with focus on economic, environmental, as well as energy efficiency objectives was developed by [138]. A framework was further introduced in [139], comparing different optimisation techniques for ship machinery synthesis and operation, concluding that linear methods are sufficient for the synthesis, while they are not suitable for the operational optimisation. Finally, a three-level optimisation of a ship propulsion system was performed in [140–142] by employing a superstructure approach and similarly in [143] with considerations of the system dynamic behaviour.

In the pertinent literature, few studies addressed the sustainability assessment of alternative marine technologies with multi-criteria analysis techniques. The performance of energy sources for shipping in environmental, social, economic and technological criteria under incomplete information was investigated in [144], ranking alternative marine technologies according to specific indicators.

Table 1 Studies on decision support for sustainable ship energy systems (PS: propulsion system (prime mover), HR: waste heat recovery, EC: emission compliance (emission abbatement technologies), TB: thermal boiler, EA: electric auxiliary system, ECN: economic, GE: gas emissions, EEDI: Energy Efficiency Design Index, EE: energy efficiency, T: technical, S: safety, AHP: Analytic Hierarchy Process, MC: Multi-criteria analysis)

| **Studies** | **Ship Energy Systems** | | | | | **Criteria** | | | | | | **Method** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Sustainability** | | | | | | |
| | **PS** | **HR** | **EC** | **TB** | **EA** | **ECN** | **GE** | **EEDI** | **EE** | **T** | **S** | |
| [111] | • | | • | | | × | × | | | | × | MC analysis |
| [144] | • | | | | | × | × | | | × | | MC analysis |
| [145] | • | • | | | | | × | | × | | | simulation |
| [112] | • | • | | | | × | × | | × | | | simulation |
| [94] | • | • | | | | | | | × | × | | simulation |
| [93] | | • | | | | | | | × | | | simulation |
| [92] | | • | | | | | | × | × | | | simulation |
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| [105] | • | | | | • | | | × | | | × | simulation |
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| [107] | • | • | • | | | × | | × | | | | simulation |
| [106] | • | | | | • | | × | | × | | | experiment |
| [85] | • | | • | | | × | | × | | | | optimisation of synthesis |
| [136] | • | • | • | • | • | × | × | | | | | optimisation of synthesis |
| [135] | • | • | • | • | • | × | × | | | | | optimisation of synthesis |
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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [103] | | • | • | | | | | | × | | | optimisation of design |
| [101] | | • | | | • | | | | × | × | | optimisation of design |
| [100] | | • | | | | | | | × | | | optimisation of design |
| [99] | | • | | | | × | | | | | | optimisation of design |
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| [115] | • | • | | | | | | | × | | | optimisation of design |
| [124] | • | | | | • | × | | | | | | optimisation of operation |
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| [125] | • | | | • | • | × | | | | | | optimisation of operation |
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| [134] | • | | | | • | | | | x | | | optimisation of operation |
| [122] | • | • | | | • | | | | × | × | | optimisation of operation |
| [126] | • | | | • | • | × | × | | × | | | optimisation of operation |
| [102] | | • | | | | | | | × | × | | optimisation of design &operation |
| [146] | • | • | • | • | • | | | | × | | | optimisation of operation & synthesis |
| [139] | • | | | | • | | | | × | | | optimisation of operation & synthesis |
| [138] | • | • | | • | • | × | × | | × | | | optimisation of design & synthesis |
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| [142] | • | | | | • | × | | | | | | optimisation of operation & design & synthesis |
| [140] | • | • | | | | × | | | | | | optimisation of operation & design & synthesis |
| [81] | | | • | | | × | × | | | × | | simulation & MC (AHP) |
| [97] | | • | | | | × | × | | | | | MC analysis & optimisation of design & operation |
| [110] | • | | | | | × | × | × | | × | | simulation & MC (AHP) |

# 4 Discussion

A detailed review of 95 studies has been performed targeting to provide a comprehensive overview of the decision support methods for enhancing ship energy systems sustainability published in the pertinent literature. The aim of this review was to identify the research gaps and the trends on supporting decisions for ship energy systems with consideration of sustainability objectives. It was identified that a variety of alternative technologies and fuels can enhance the ship sustainability. A need for methods that can support the decision maker in the decisions related with the synthesis of the configuration, design and operation with sustainability considerations is recognised. The existing studies in the pertinent literature were discussed according to the employed method, the considered systems and the criteria used for the assessment.

## *4.1 Key findings and trends on the methods used for the decision support of ship energy systems sustainability*

Figure 3 shows the types of methods, adopted for the decision support of ship energy systems synthesis, design, operation to improve the ship sustainability. It is evident that optimisation, life cycle assessment and simulation methods are dominant, whereas analytical methods or experimental are adopted in a limited extend.

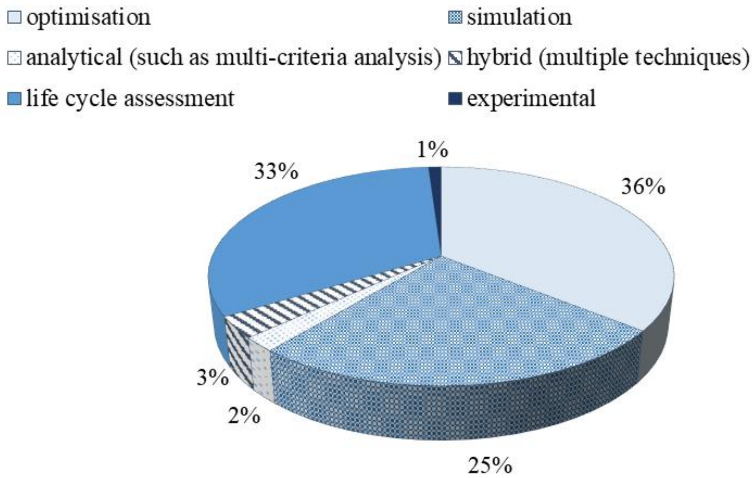


Figure 3. Classification of methods

LCA studies have been used to primarily assess specific ship energy system configurations or to compare among a limited number of options. In this sense, LCA is useful for assessing individual or small number of configurations; however, LCA cannot easily support complex decisions in terms of optimising the system design or operations. LCA has inherent limitations as a method, and although it has been used to assess the ships environmental sustainability, it is acknowledged that this method is not quite compatible with ships [8,147] or has to be used with caution [44]. Currently, there are no available databases to support LCA in shipping, so the databases of the land-based power plants have been employed. As argued in [147], some parts of the LCA methodology are not consistent with sea transportation, thus, leading to inaccurate results. Another issue is that in the maritime sector, there is no model available for assigning the emissions calculated in the inventory phase of LCA, to the midpoint impacts [51]. This process requires specifying the location and if such information is not available, it is not possible to evaluate the impact of emissions [52]. This constitutes an obvious challenge for shipping, since emissions do not occur in a specific geographical location. It is also highlighted that information on emissions from some processes on the dismantling/recycling phase are generally not available [51]. Previous studies supported that the existing LCA software tools cannot meet the specific ship design requirements [46], as many simplifications and assumptions need to be made for complex ships systems. The LCA impact categories are too generic, and some polluting agents are not identified by the employed categories. Thus, it is identified that the majority of impact assessment methods do not manage to address the sustainability of marine technologies [9,148,149]. The focus of most of these studies was on the environmental aspect of sustainability; sometimes the economic aspect was integrated, whereas the social dimension was considered only in very few cases. The challenges to perform LCA and assess the social impact in shipping were acknowledged. Finally, impact categories and databases need to be developed that will reflect the environmental and social impact of marine technologies [9].

The significance of simulation models to evaluate the steady state performance as well as the transient response of the investigated ship energy systems was also demonstrated. Models of various types were identified in the literature, with the most typical being the mean value models, the zero/one-dimensional models, combinations of these two types, and three dimensional models [113,150]. In addition, a variety of thermodynamic and energy flow models were identified in the literature. To that end, simulation models were developed for the main engine as well as the emissions reduction technologies. Similarly to the LCA, the existing simulation models are developed and refer to a specific system configuration, as opposed to optimisation methods that can be used to compare a variety of configurations.

Regarding the optimisation methods, it is inferred that they are frequently used to support decisions for the ship energy system regarding operation, design and synthesis. However, even though the benefits of multi-objective optimisation for supporting decisions for sustainable ship energy systems were discussed in previous studies [10], it was identified that in the majority of the cases the studies employed a single objective and only in very few cases, a multi-objective optimisation approach was considered. It is also highlighted that most of the multi-objective optimisation approaches focused on the design optimisation regarding the sizing of the components, whereas very few studies performed multi-objective optimisation for the synthesis or operation of the ship energy systems due to the problem complexity.

The performed analysis highlighted another important aspect for the decision support methods pertaining to the significance of taking into consideration the prevailing operating conditions, due to their impact on the decisions for the ship energy systems synthesis and design phases, as discussed in [141]. The performance of the systems was assessed based on typical operating profiles assuming representative operational modes including sailing (ballast, laden), and loading in port or in some cases a variable operating profile, including all the potential off-design conditions. An expected operating profile with both design and off-design conditions was employed in operational optimisation in [88,126] as well as in few studies focusing on synthesis decision support [135,136,145], indicating the importance of the variable profile inclusion in the optimisation process.

### *4.2 Key findings and trends on the criteria used for the decision support of ship energy systems sustainability*

The criteria used for decision support derived from this review and their quantification as percentage among the identified studies are presented in Figure 4. Figure 5 provides further break down of these criteria into subcategories. It is inferred that the environmental criterion is used in the majority of the studies followed by the economic criterion. This is attributed to the extensive number of the LCA studies found in the pertinent literature. In addition, the energy or exergy efficiency is frequently used as an objective, as improving the energy efficiency of the systems leads to decreasing the operational cost and the gaseous emissions.

The gaseous emissions criterion is vital for evaluating the ship energy systems, and thus, this criterion is highly considered when supporting decisions on the ship systems sustainability, as it is evident from Figure 5. It can be deduced that the greatest focus has been placed first on the carbon emissions and then the SOx or NOx emissions, whereas limited attention has been put on the Particulate Matter (PM) emissions, even though they pose serious adverse effects on the human health and the environment. This is attributed to the fact that limitation targets for PM have not been put in force [151] yet, although IMO highlighted their hazardous effects. Furthermore, it should be noted that the minimisation of the gaseous emissions was included in the objective function of the optimisation methods only in few cases, whereas in most of the identified studies, only the potential of the various solutions to reduce emissions was assessed.

Regarding the economic aspect, it is evident that there are various criteria used to assess this aspect of sustainability, with the life cycle cost perspective having the lead. In addition, there has been great interest on the fuel and operational costs, as they constitute the greatest contributors of the ship life cycle cost.

Technical criteria were also considered in various methods, focusing on the engine performance characteristics or the weight and dimensions of the power plant components, thus evaluating the impact of new technologies on the engine room arrangement. On the other hand, safety and reliability were addressed only by three studies. The consequences and likelihood of potential accidents related to the fuel system was discussed in [111], the power plant availability and the frequency of black out were assessed in [137], whereas the system availability was investigated in [105]. Finally, a growing interest to incorporate the EEDI index in the assessment process can be inferred.

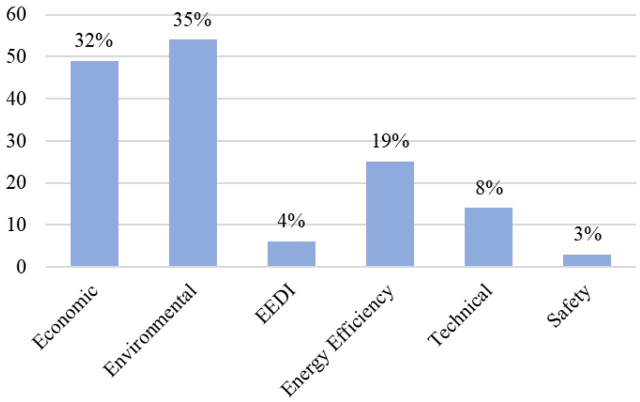


Figure 4. Quantification of criteria identified on the studies

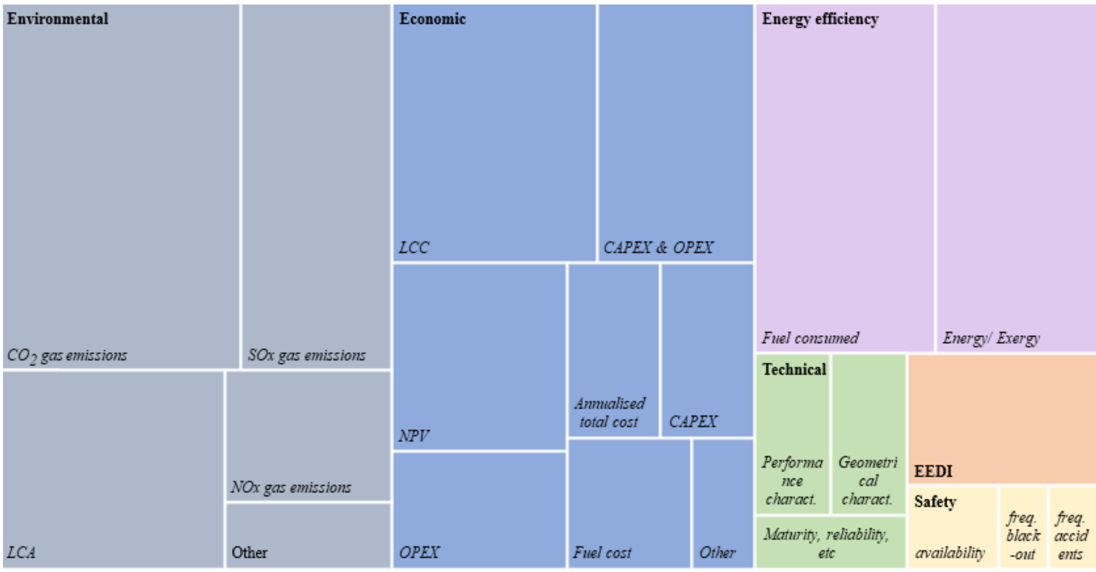


Figure 5. Analysis of Criteria in sub-categories with cell area denoting the percentage of each category on the total number of identified studies (CAPEX: Capital expenditure, NPV: Net Present Value, OPEX: Operational Expenditure)

Moreover, the positive association patterns between the different pairs of criteria employed by the decision support methods are estimated. Figure 6 illustrates the ratio of the observed frequency of each pair of criteria towards their statistical expected frequency, which was calculated according to pair-wise comparisons, as reported in [152]. Some pairs have higher than expected frequency, such as the economic-environmental, the energy efficiency-technical, and the environmental-technical, thus indicating a reinforcing association. These categories are often addressed simultaneously, which is justified by the fact that until recently economic, technical and energy efficient issues were at the forefront of the ship systems design research. However, due to the recent stringent regulations the environmental concerns have also attracted attention. Other pairs related with safety (i.e. the environmental-safety or the EEDI-safety) indicate a higher than expected frequency; this is due to the fact that overall, in the literature there were very few occurrences where safety was considered and the sample was quite small in order to identify a clear causal relationship. Other pairs such as environmental-EEDI or energy efficiency-economic, showcase a moderate association, which arises from the fact that the former pair focuses on the emissions, whereas for the latter pair, both criteria are associated with the fuel cost reduction, thus they are avoided in order to prevent the double counting.

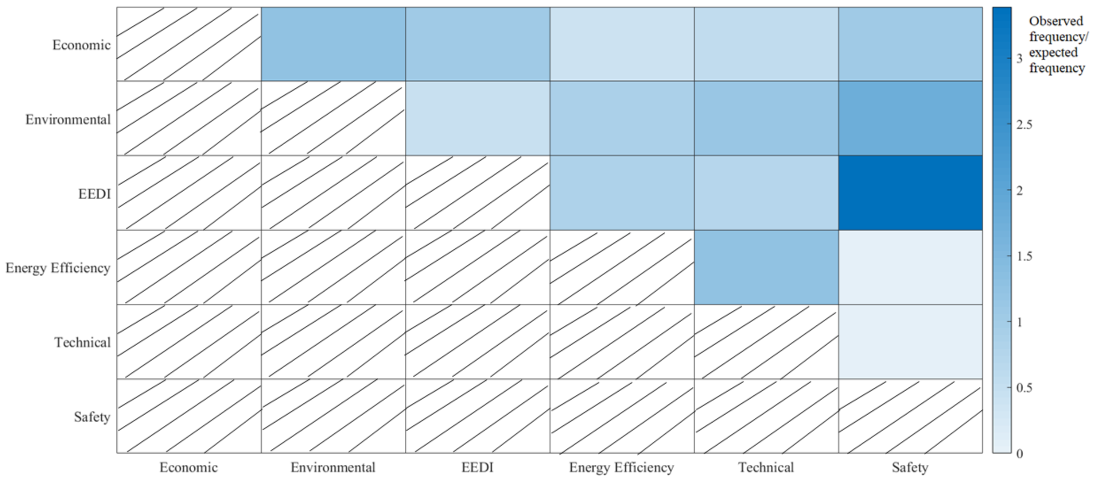


Figure 6. Positive association patterns between criteria

The social aspect of sustainability is considered only in few of the studies, when LCA is employed.  There are various social sustainability assessment tools, like Social Life Cycle Assessment; however, only a few cases assessing the social impact of marine technologies were found in the pertinent literature [9,153]. Most of the existing social impact assessment tools are based on subjective assumptions [8], which leads to two drawbacks. First, it is challenging to aggregate and compare the social impact assessment tool results with the results of the other dimensions of sustainability, since for the former, the results are mostly qualitative, whereas quantitative metrics are calculated for the other sustainability dimensions. Secondly, due to the nature of the social impact assessment tools that are highly based on the user's input through questionnaires or interviews, the results might be considered biased and subjective [9].

### *4.3 Key findings and trends on the energy systems and technologies used for the decision support of ship energy systems sustainability*

It is highlighted that there are limited studies considering the integrated ship energy systems. The majority have focused on the assessment of one or two specific components, the assessment of a specific predefined propulsion system, or, in few cases, the comparative assessment of a limited number of potential alternatives. The greatest part of the literature focuses on the propulsion systems and the waste heat recovery from the exhaust gas of the ship main engines, as it is revealed from Figure 7. This is also highlighted in Figure 8, which depicts the methods used to support decisions for the different components. Optimisation methods focus mostly on the propulsion plant and electric auxiliary systems, whereas the simulation methods have mostly been used to represent the waste heat recovery, the emissions abatement technologies, and the propulsion plant system and their components.

The auxiliary electric system has been gaining attention, due to the interest on the design or the operational optimisation of hybrid configurations or other alternative technologies, such as fuel cells or solar panels. The emissions reduction technologies are included in various studies to evaluate the associated emissions reduction potential from the ship main engine, whereas the thermal auxiliary boiler is considered only in limited studies. On few occasions, the prime mover is also assessed and optimised along with the ship propulsor.

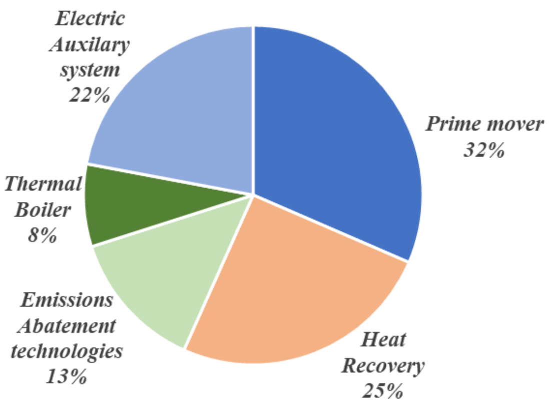


Figure 7. Considered systems in the reviewed studies

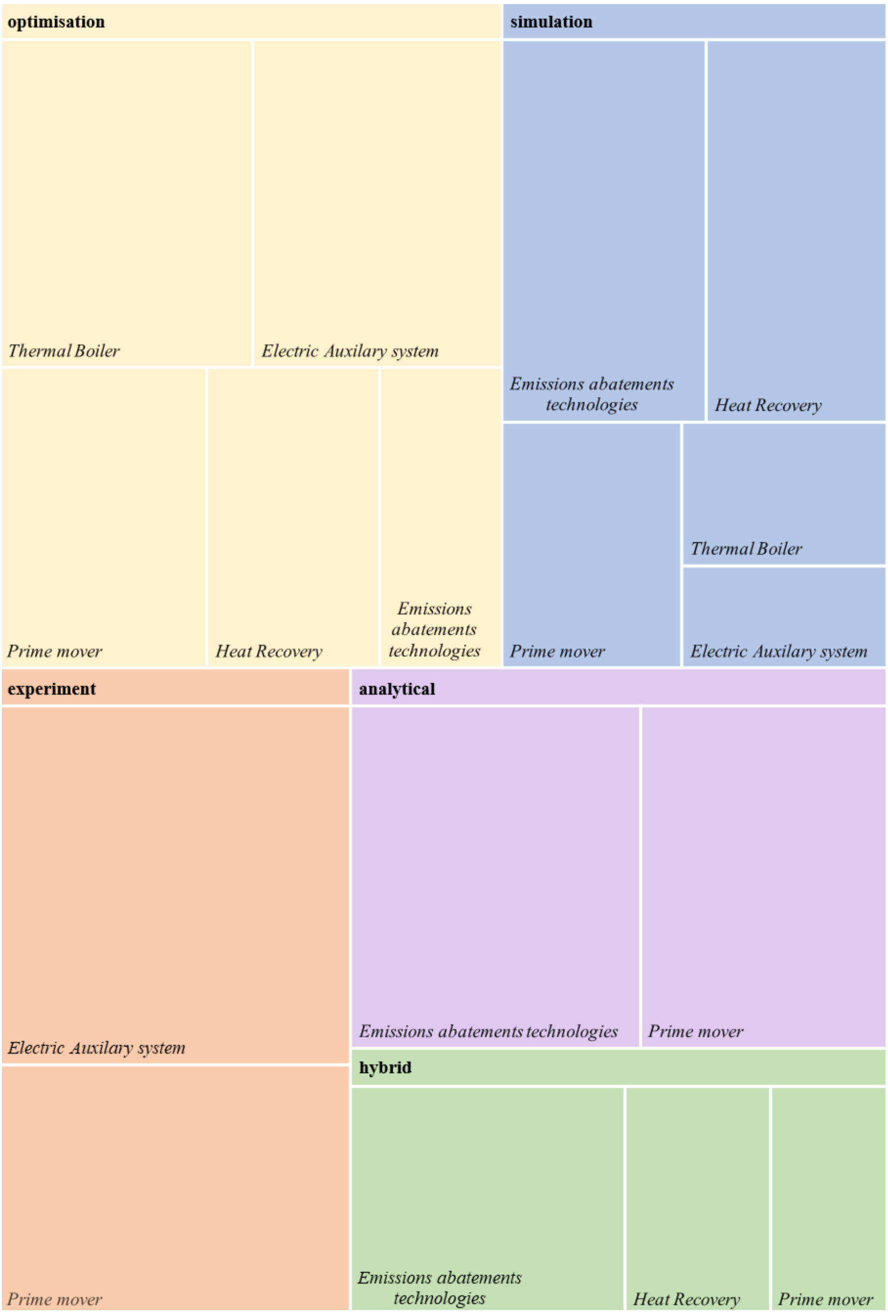

Figure 8. Analysis of susbsystems considered on the various methods with cell area denoting the percentage of each category on the total number of the identified studies

Moreover, this review study demonstrates that recently the focus has been placed on the more complex hybrid configurations that include among others batteries and fuel cells. These systems can improve the environmental footprint and the energy efficiency of ship energy systems. However, there are further challenges that need to be addressed, which are related to the commercialisation of these technologies and their potential for shipping applications in the medium- to long-term basis. According to [154], for vessels operating with high energy demand for long periods without connection to a land-based electric grid, power plants based on fuel cells are preferred from battery-based technologies due to their relatively lower cost and specific weight (compared to batteries).

From the analysis of the identified studies, it is also derived that the complexity of ship power systems with microgrids has been increasing recently, especially for all-electric ship systems [128]. In the latter case, the ship electric grid resembles islanded microgrids, but with more varying dynamic conditions and higher load changes as well as at a wider operating envelope [129]. Therefore, energy storage systems have been proposed as a promising solution to handle transients on ship microgrids, whereas various strategies for energy storage management can be employed; however, criteria related to the technologies' power and energy density have to be considered when selecting the optimal alternative [129].

Furthermore, the innovative changes on the power grid lead to increasing advancements in power electronics converters [132] and complex systems that will challenge the future ship power plant design and operation management. Therefore, there is a need for design, optimisation and control of these complex systems and the design of suitable energy management power or storage systems that will improve the energy efficiency of the ship [127,129]. In specific, it is indicated that special attention is required on optimisation methods of real-time control of the lower-level components to the higher system level control, as well as on accurate load forecasting methods for all electric ship power plants. In this respect, a real time balance of supply and demand can be achieved, which can lead to power system stability.

Finally, with the increasing attention on alternative fuels, there is a shift to include other systems along with the traditional ship energy systems. For example there is great interest in optimising the fuel gas supply system of liquified natural gas (LNG) in order to find the optimal boil off gas configuration [122].

## 5 Concluding remarks and recommendations for future research

The present review study analysed the published studies investigating the decision support systems for enhancing the ship energy systems sustainability. A variety of studies was reviewed, and the key findings and trends were identified and discussed. This analysis demonstrated that the interest on ship energy systems sustainability exhibited an exponential increase the last decade. However, there is still space for improvement. The recommended areas for future investigations are illustrated in Figure 9 and delineated in the next paragraphs.

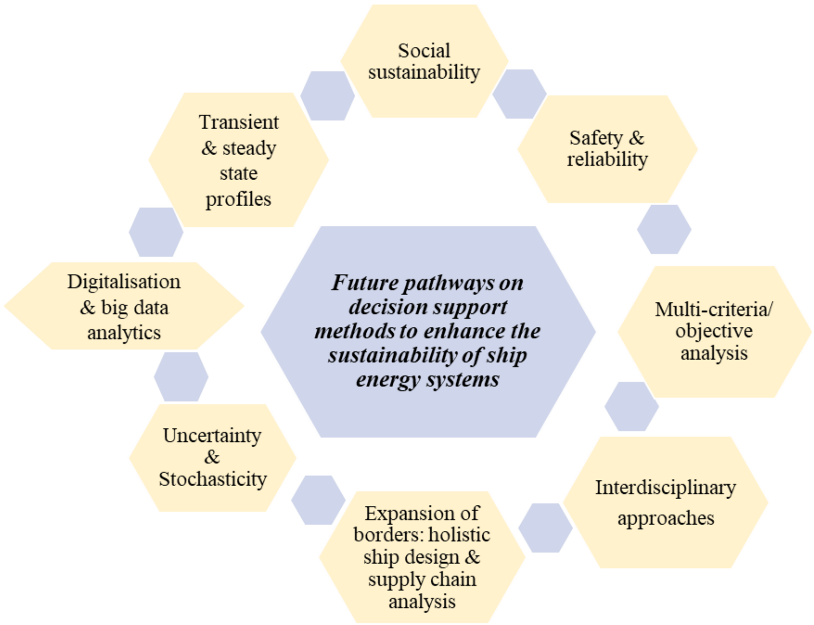


Figure 9. Future pathways on decision support methods to enhance the sustainability for ship energy systems

The social aspect of sustainability, which expresses the assessment of the effects of the ship energy systems on the society, requires further investigation to overcome challenges pertinent to the offshore nature of the shipping industry. The social assessment tools presently cover land-based activities and the social impacts are influenced by the location and the socio-economic situation [9]. In this respect, the existing tools need to be customised for application to shipping operations [8].

Furthermore, the introduction of safety and reliability metrics is crucial for the selection and design of safe and sustainable ship energy systems. It is quite important to introduce appropriate safety metrics in the criteria considered, especially with the recent attention placed on zero carbon fuels, such as hydrogen and ammonia, which introduce new hazards and impact the system safety. Additionally, reliability is an objective that is typically omitted at the decision support stage and is empirically assessed afterwards, thus resulting in 'non-optimal' solutions [38].

With regard to methodological future improvements, it was inferred from the preceding analysis that the majority of the decision support methods employed a single criterion/objective, despite the fact that when supporting decisions for enhancing the ship energy system sustainability, trade-offs among the criteria are required to identify the most sustainable option [155]. Hence, these decision support approaches cannot define truly sustainable ship energy systems. Multi-criteria decision making methods have been identified as an appropriate tool for sustainability in the land energy sector and have been extensively used in the pertinent literature [155–158], however for the ship energy systems these methods are not yet widely employed.

The majority of the methods presented in the pertinent literature focused on the main ship energy systems excluding the ship service systems, such as the ventilation and air conditioning system. Furthermore, there exist limited studies that consider the energy systems along with the hull, and the ship propulsor, whereas in the few cases following a more integrated approach, the main focus was the on matching the prime mover with the propulsor. In addition, advancements are observed on ships electrification, as a result of hybrid and all-electric ships, thus leading to interdisciplinary approaches regarding the decision support for ship power plants, with focus on electrical and control optimisation [38]. Therefore, an expansion regarding the systems considered for the ship power plant is observed, in addition with the optimisation methods required for decision support. It is significant to incorporate the interrelationships between the different systems in the decision support methods, thus expanding the borders of the analysis, therefore moving towards a 'holistic way' [159], which can ultimately lead to a more optimal system design.

The majority of the decisions made for the energy sector are significantly affected by data uncertainty [160]. In shipping, there is great uncertainty in fuel and emerging technologies prices, as well as in the load profile. These uncertainties might lead to suboptimal decisions, when the assumed parameters differ from the ones in reality, as well as changes to the values of the model parameters might lead to the solutions 'instability' [161]. The degree to which a solution is insensitive to the environment is defined as the robustness of a solution [162]. When the robustness of the optimal solutions is not included, then, it is possible for the decision maker to select a solution that is very sensitive to the parameters of the model. Therefore, it is significant to incorporate these uncertainties, either with a posterior sensitivity analysis [135] or by taking into consideration these uncertainties during the optimisation [38].

As it was highlighted from this review, it would be important to develop a set of typical operating profiles for different ship types that will be used for the performance assessment of the ship energy systems. However, the available data in academic sources is limited and confidentiality issues do not support easy access to the industry sources. Moreover, in the limited cases where the operational data are recorded shipboard, they need extensive analysis to filter outliers, thus confining inaccuracies. Furthermore, the transient operation is usually ignored and only the steady-state conditions are considered, due to the fact that the former is very short in time. However, a dynamic operation of the system would be necessary for supporting decisions on the power plant configurations that include batteries. This increasing need for data gathering and analysis could be supported by the rapid development of big data acquisition and analysis. In addition, with the digitalisation advancements, there is rapid progress in real-time monitoring of different performance parameters, such as temperature, speed, emissions [163] as well as the shaft instantaneous torque [164]. These inputs could have a significant impact on the decision support methods and consequently, on the autonomous ships design [165].

Finally, during the quest for decarbonisation alternative zero-emissions fuels are considered, especially since it is supported that the IMO 2050 targets will only be reached if carbon-neutral fuels provide 30-40% of the total energy [166]. Many studies focus on the environmental benefits of these fuels during the ship operation; however, it is crucial to address the life cycle performance of these types of fuels and specifically the production stage, thus expand the supply chain analysis. Therefore, it is important to move towards zero carbon emissions, where the fuels are produced by using renewable energy sources or employing carbon capture [2]. However, this is not a straightforward process, for example producing green ammonia to cover the international shipping fleet requirements will need 6500 TWh of electricity provided by renewable sources, which is almost as much as the electricity requirements in China [167]. As a result, future issues that need to be addressed include the viability of such supply chains.

Concluding this study, it is highlighted that the maritime industry faces huge challenges due to the explosion in technological developments, the marine systems complexity and its conservatism, whilst operating within an environment that becomes increasingly sensitive and a demanding society. Future research studies need to employ novel scientific multidisciplinary approaches to holistically account for the interplay between all aspects of the sustainability paving the way towards the design and operation of the next generation of ship energy systems.

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